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1842 ELECTRONICS ENGINEERING GROUP

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The 1842 Electronics Engineering Group (EEG) is organized as an independent group reporting directly to the Commander, Air Force Communications Service (AFCS) with the mission to provide communications-electronics-meteorological (CEM) systems engineering and consultive engineering for AFCS. In this respect, 1842 EEG responsibilities include: Developing engineering and installation standards for use in planning, programming, procuring, engineering, installing and testing CEM systems, facilities and equipment; performance of systems engineering of CEM requirements that must operate as a system or in a system environment; operation of a specialized Digital Network System Facility to analyze and evaluate new digital technology for application to the Defense Communications System (DCS) and other special purpose systems; operation of a facility to prototype systems and equipment configurations to check out and validate engineering-installation standards and new installation techniques; providing consultive CEM engineering assistance to HQ AFCS, AFCS Areas, MAJCOMS, DOD and other government agencies.

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This document is to provide basic engineering information about EMP. Emphasis in this document will be on EMP protection guidelines. Information presented is designed to assist engineers in familiarizing themselves with EMP and EMP Problems.

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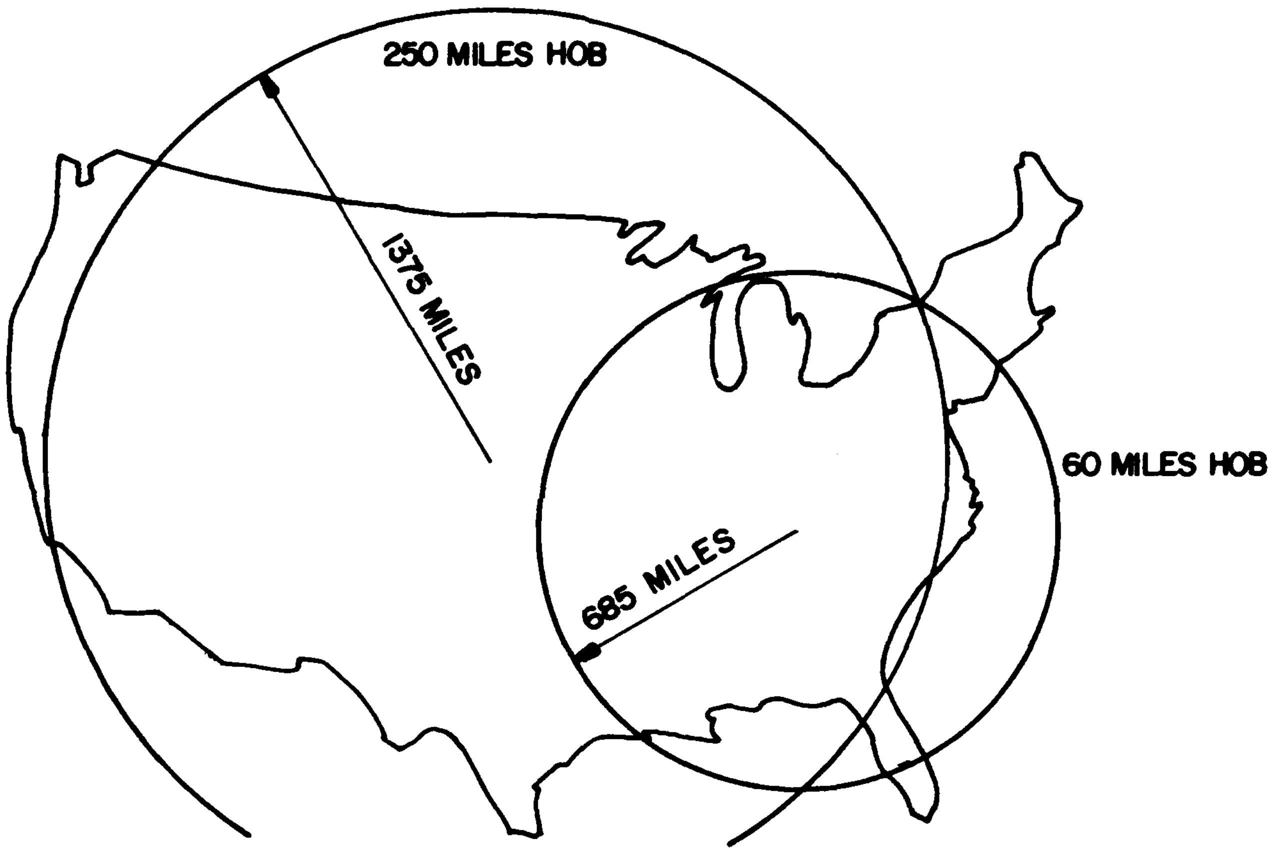
EMP HANDBOOK

A. INTRODUCTION. An area that very few C-E-M engineers are aware of is the effects on our communication systems in the event of a nearby nuclear explosion. One effect that was found is that under the proper circumstances, a significant portion of the energy released during a nuclear detonation can be made to appear as an Electromagnetic Pulse (EMP) having the same frequencies as our commercial radio and military communication systems. This document will investigate this phenomenon and provide typical engineering information that must be considered to provide adequate protection from EMP in any military communication system. The engineering information to be provided is, in most cases, familiar terminology and closely ties into EMC/EMI protective procedures. Engineering principles are similar to ones in use today and will be most familiar to engineers with EMI/EMC experience. One of the primary reasons why EMP has great interest today is the fact that EMP is capable of disabling electrical and electronic systems as far as 3000 miles from the site of the detonation. This means that a high yield nuclear weapon burst above the atmosphere could be used to knock out improperly designed electrical and electronic systems over a large area of the earth's surface without doing any other significant damage. Figure 1 shows this situation.

Another point of concern in EMP is the strong electromagnetic field created. An idea of the amplitude of the EMP electromagnetic field can be gained when compared with fields from man-made conventional sources. A typical high level EMP pulse could have an intensity of 100,000 volts per meter. This is 1,000 <u>times</u> more intense than a radar beam of sufficient power to cause biological damage such as blindness or sterilization.

B. PURPOSE. This document is to provide basic engineering information about EMP that is presently available. EMP is a large and complex subject and this document will not delve into involved mathematical investigations but general information. Emphasis in this document will be basic EMP protection guidelines. The information presented is designed to assist engineers in familiarizing themselves with EMP and EMP problems. This handbook will be basically a compilation of existing data on EMP and only portions that may be of interest or of importance are included. A comprehensive bibliography will be included for further reference.

HOB-HEIGHT OF BURST



AREA OF COVERAGE OF EMP FROM HIGH-ALTITUDE DETONATIONS

FIGURE 1

C. ELECTROMAGNETIC PULSE GENERATION AND EFFECTS

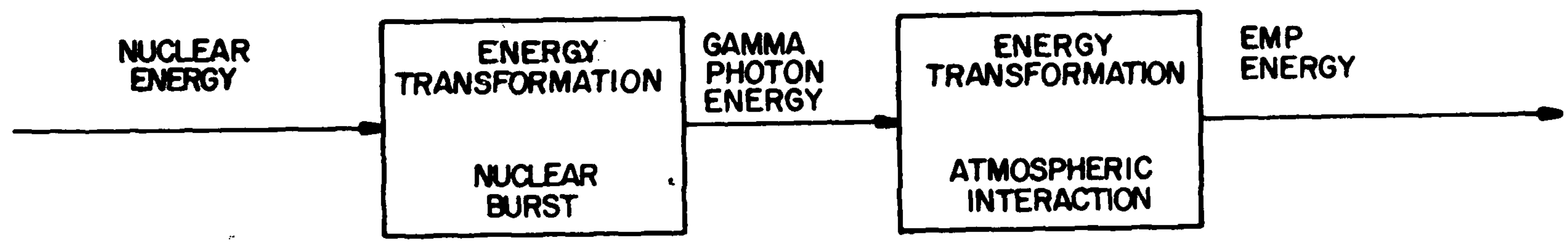
1. EMP ENVIRONMENT DESCRIPTION. A nuclear detonation generates large amounts of energy which can be grouped in such categories as blast, thermal radiation, nuclear radiation, and electromagnetic pulse (EMP). This chapter provides an introduction to EMP generation and effects.

1.1 EMP Phenomenon. A fundamental phenomenon exists which creates the electromagnetic pulse. The basic mechanism is electron scattering by the collision of gamma rays with air molecules or other materials. The collision knocks electrons free of the air molecules and causes the electrons to move rapidly away from the center of the explosion and from the now positively charged parent air molecules. This separation of charges, occurring on a wholesale basis, creates electromagnetic fields. An energy flow diagram which illustrates the transformation of energy involved in the process of EMP generation is shown in Figure 2. The energy released from a nuclear burst in the form of gamma ray photons interacts with the earth's atmosphere to produce electrons and positive ions. The separation of electrons and positive ions produces an electric field. The flow of electrons constitutes a current which radiates electromagnetic energy, providing some asymmetry exists.

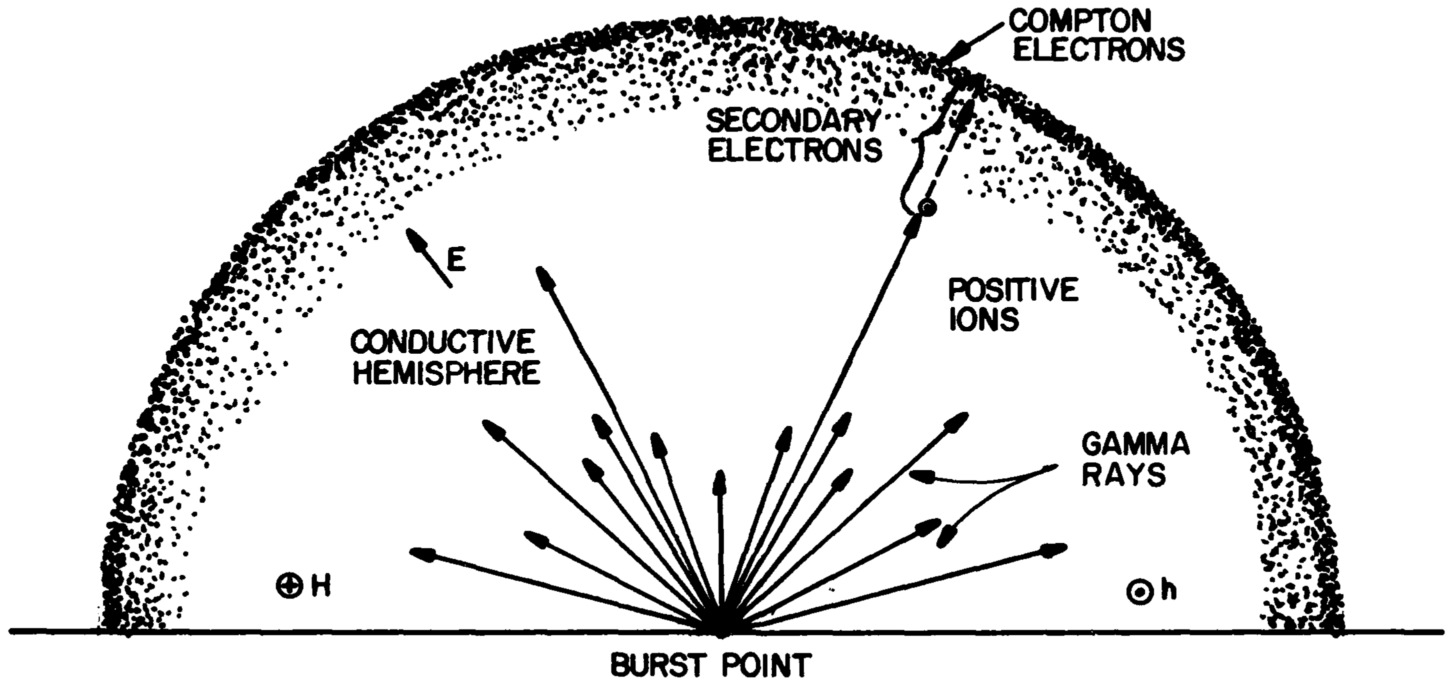
The energy contained in EMP is similar to that in EM waves generated by a lightning strike, but the high frequency energy content in EMP is a much larger fraction of the total pulse energy.

1.2 NUCLEAR WEAPON EFFECTS. The relative importance of all nuclear weapons effects, including EMP, depends on weapon characteristics, burst point, and position of the system of interest. Emphasis in this document will be the EMP fields generated by a high altitude burst and some discussion about surface bursts.

1.2.1 Source Region. For both the high altitude and surface bursts, intense fields appear in what is called the source region. The source region for a surface burst is limited to about a two to ten kilometer diameter about the burst. Figure 3 illustrates a surface burst. For a high altitude burst, the source region can be on the order of 3000 kilometers in diameter. Figure 4 illustrates a high



ENERGY FLOW DIAGRAM
FIGURE 2



SURFACE BURST

FIGURE 3

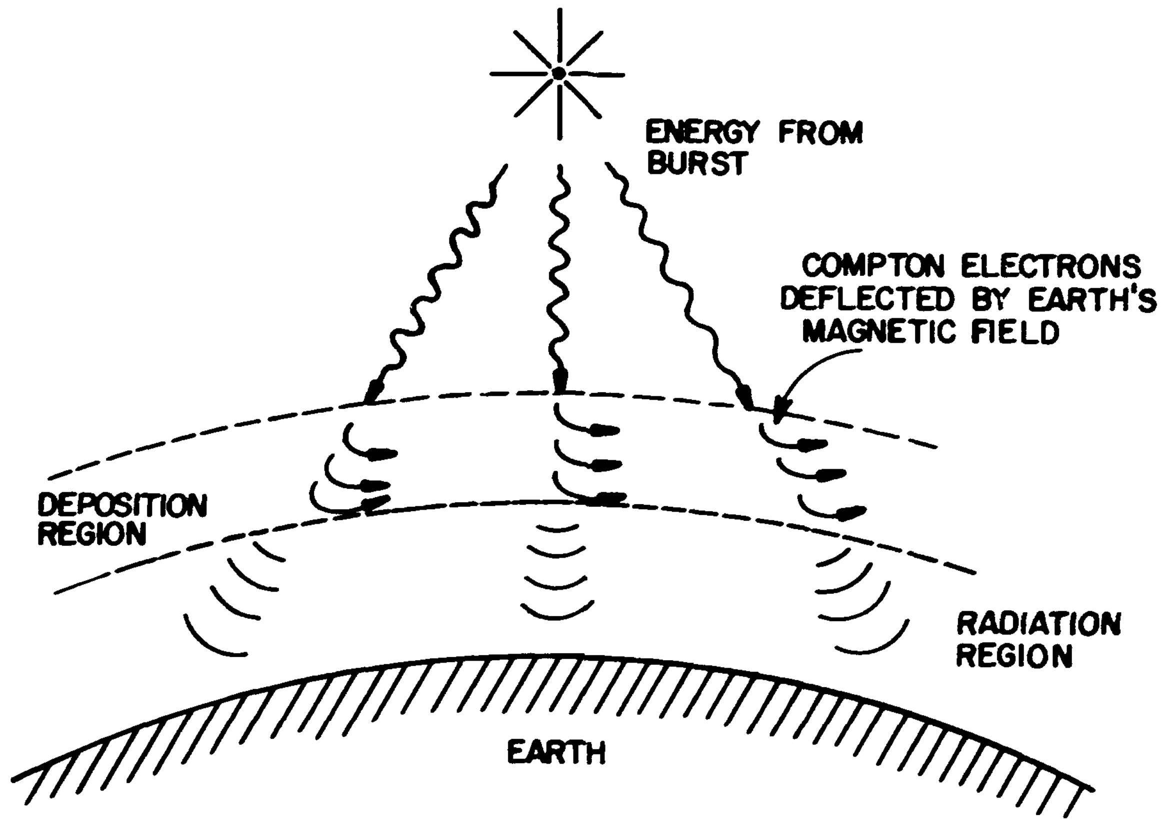


ILLUSTRATION OF THE BASIC GEOMETRY OF THE HIGH-ALTITUDE BURST

FIGURE 4

altitude burst. This source region extends from about 20 to 40 kilometers in altitude. In the source region, weapon effects other than EMP must also be considered. As noted, the size of the source region is severely confined by the atmosphere for an atmospheric burst. However, the pressure pulse, which physically damages the buildings, is not similarly restricted. Thus, in the case of soft systems (buildings), the most severe EMP exposure at otherwise survivable points is associated with the low-yield bursts.

1.2.2 Fields Beyond Source Region. Somewhat less intense fields exist beyond the source regions. Additional mechanisms exist to radiate the energy of the source fields well beyond the source regions. In the case of a near-surface burst, the net charge separation caused by asymmetry of the source region contributes to the more distant radiated fields. In an outside-the-atmosphere burst, the earth's magnetic field bends the scattered electron current moving away from the burst point. This bending produces an efficient conversion of the energy of the moving electrons into a radiated electromagnetic pulse in the radio spectrum. This radiation is propagated from the source region onto the surface of the earth. In the case of a high-altitude burst, a significant overpressure pulse does not exist near the surface of the earth. Almost all of the other prompt weapon effects are diminished by the atmosphere, so that the most significant prompt weapon effect is the EMP. As noted previously, the source region can be quite large, in the order of 1,000 miles in diameter. As a consequence, the radiated fields from this source region can cover a substantial fraction of the earth's surface.

1.3 Comparison with Lightning. One method of assessing the impact of this electromagnetic pulse from a nuclear detonation is to compare the phenomenology of a nuclear explosion to that of a lightning strike. In the case of both the lightning strike and the nuclear detonation, only a fraction of the total energy is released in the form of electromagnetic radiation. The total energy radiated from a large nuclear detonation, however, can be many orders of magnitude greater than the energy radiated from a lightning strike. Thus, while the most familiar result of the electromagnetic radiation from a lightning strike is radio-static, the results from a nuclear burst would not only cause static but could be capable of damaging sensitive electronic components. In terms of waveshapes, it is not possible to draw explicit comparisons. In the case of

lightning strikes, the rise times vary widely; and by normal time intervals, little time elapses before full field intensities are reached (microseconds). However, many of the rise times associated with nuclear events can occur in much shorter intervals (nanoseconds). It can be assumed that these very fast rise times can also occur for nuclear-created electromagnetic environments, although wide variations from this are possible. Thus, the amplitudes and waveshapes of the EMP can be considerably different from those of lightning. Another important difference is the spatial distribution of the electromagnetic environment. In the case of EMP, this environment is widely distributed; however, in the case of lightning strikes, the most severe effects are quite localized. An additional important consideration is the timing of the appearance of these high-energy environments. In the case of EMP, this high-energy environment occurs nearly simultaneously over large areas (the only limitation being the speed of light). On the other hand, in the case of lightning strikes, these high-energy environments seldom appear simultaneously over wide regions. The amplitude of the EMP can also be expected to exceed the normal electromagnetic environment created by nearby broadcast stations. Other obvious differences exist here, since the broadcast station radiation is more or less continuous--whereas the EMP occurs as a short duration burst of energy. The above discussion points up the major differences that exist between normally occurring electromagnetic environments and the electromagnetic pulse created by a nuclear detonation. For certain situations, the amplitude of the EMP can exceed by several orders of magnitude, this "normal" environment. The most severe EMP environment for a hardened complex, such as a carefully hardened shelter, can occur within the ionized sphere or source region. The radiated environments at a distance are obviously less severe than those found in the source region. The radiated EMP environment is of significance, however, since it can appear and must be considered over large geographical areas. In Section C, a brief explanation of EMP phenomenon was discussed; however, to get a better feel of EMP, it is necessary to go back to basic atomic physics and investigate EMP phenomenon from this standpoint. This section will attempt to explain from an atomic physics standpoint EMP, what causes EMP, and the magnitude of EMP pulse.

2.1 BASIC ATOMIC AND NUCLEAR PHYSICS. The structure of an atom can be visualized in the familiar form of a small, positively charged nucleus surrounded by an electron cloud. The electron cloud is held in place by the electric coulomb attraction between the nucleus and electron. The nucleus is on the order of 10^{-12} cm in diameter, while the electron cloud is about four orders of magnitude larger. The nucleus is made up of protons (single positive) and neutrons (zero charge). The nucleus is held together by intense, short-range forces which are not yet completely understood. These nuclear forces are so strong that they overbalance the electric coulomb repulsion of the protons for each other. Atoms and nuclei exist in states having certain discrete energies. This is the basis for the quantum theory developed by Bohr, Planck, and many others. This theory gives a complete explanation of chemistry and atomic physics. There can be no doubt of its essential correctness. The energy difference of electron levels is of the order of a few electron volts. An electron can fall from one level to a lower one, at the same time emitting a quantum of light (proton). The energy lost by the electron is carried away by the light quantum. For example, "green" light quanta have energy of about 2.5 electron volts. An electron volt is the kinetic energy gained by an electron when it is accelerated through a potential of one volt. The energy difference of proton levels in a nucleus is of the order of a few million electron volts. A proton can fall from one level to a lower one, at the same time emitting a gamma ray (photon). Again, energy is conserved. There is no difference between gamma rays and light quanta except that gamma rays have about a million times more energy per quantum. Gamma rays are the principal cause of EMP. About 0.1% of the energy of a typical nuclear bomb appears as prompt gamma rays. How does this happen? In order to answer this question, the fission process must be investigated.

To start with, consider the action of protons. The protons in a nucleus repel each other electrically. In a spherical nucleus, the electric repulsion is overbalanced by the nuclear forces. Ordinary nuclei are held spherical by a surface tension. In large nuclei, the surface tension is not srong enough to keep the nucleus spherical. The electric repulsion tends to make the nucleus elongate, eventually dividing into two roughly equal parts. This is the fission process. This is one of the basic reasons why nuclei larger than uranium do not exist in nature; they

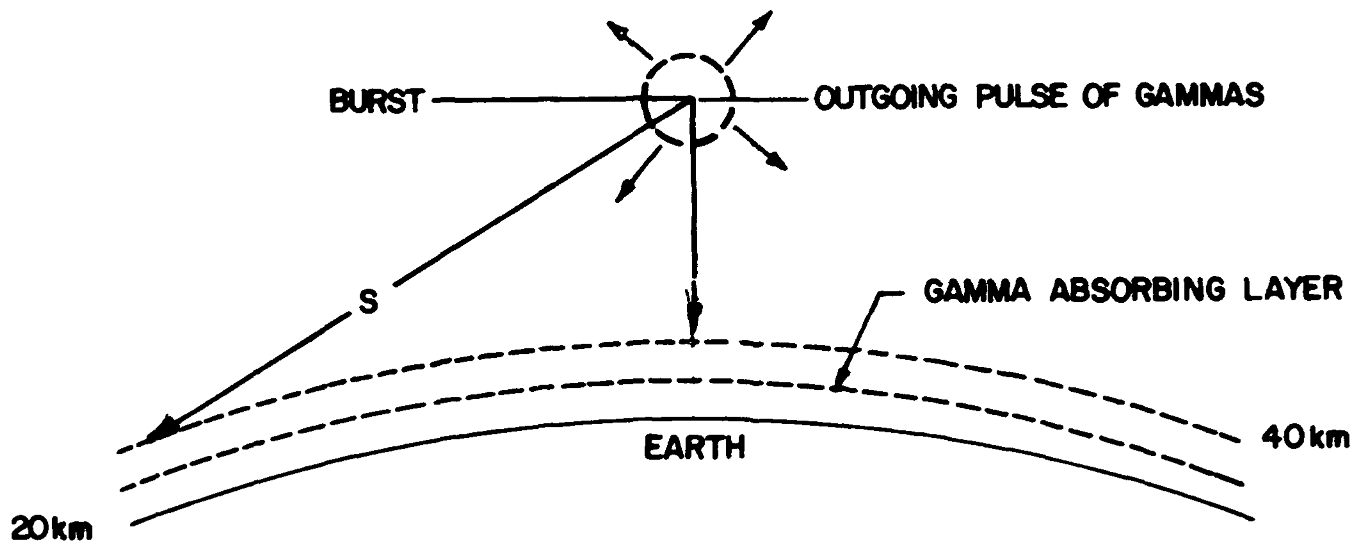
are unstable against fission. Some nuclei, like U^{235}, are just on the verge of being unstable. If such a nucleus is hit by a free neutron, it may undergo fission. The fission process is not neat and tidy as a few free neutrons get lost in the rush. These freed neutrons may hit other U^{235} nuclei, causing them to fission. On the average, a free neutron travels about 10 cm before striking another U^{235} nucleus and making it fission. If the piece of U^{235} is too small (sub-critical), the freed neutrons will escape without causing further fissions. If the piece of U^{235} is large (super-critical), the number of fissions will grow exponentially with time, with the number of fissions proportional to $e^{t/\tau}$. The enfolding time, τ, is approximately equal to the travel time of a freed neutron before hitting another U^{235} nucleus. This time is in the order of 10 nanoseconds. The EMP can have comparable rise time. Where do gamma rays come from? The fission fragments are usually not born in their ground levels. Free neutrons collide with other nuclei in the bomb or air or earth, knocking some of these into levels above the ground level. Gamma rays are then emitted in transitions back to the ground level.

3. *GAMMA RAYS CAUSE EMP.* How do the gamma rays cause EMP? The answer is through the Compton scattering process. Compton discovered that photons can collide with electrons, knocking them out of the atoms in which they were originally bound. These Compton collisions are somewhat like the collision of a moving billiard ball with one at rest. The recoil electron, like the ball originally at rest, goes predominantly forward after the collision. Thus, a directed flux of gamma rays produces, by Compton collisions, a directed flux of electrons. This constitutes an electric current, which generates the EMP. In order for a system of radial currents to radiate electromagnetic energy, a departure from spherical symmetry is required. Anisotropy of the emission of gamma rays from a burst is small and of short duration compared with other factors. The presence of the earth-atmosphere interface provides the asymmetry for surface bursts. For high-altitude bursts, the asymmetry factor is introduced by the atmospheric density gradient and geomagnetic field. We can now consider some order of magnitude estimates of the energy involved at each stage of the EMP generation process. A one megaton bomb releases 4 x 10^{15} joules of energy. About 0.1% of this energy, or 4 x 10^{12} joules, may appear as prompt gamma rays. This amount of energy is equivalent to that produced by a hundred

megawatt power plant running for about 11 hours. A fair fraction, about one-half of this goes into the Compton recoil current. Fortunately, most of this energy goes into heating air rather than into the EMP. About 10^{-3} of the gamma energy goes into EMP; thus giving about 10^{-6} of the bomb energy going into the EMP.

4. TYPICAL HIGH ALTITUDE BURST EXAMPLE. The geometry for a high altitude burst is illustrated in Figure 5. In this illustration, the height of the burst is taken as 400 kilometers or 250 miles. For this height of burst, the distance to the horizon is 2250 kilometers, or 1400 miles. The resulting EMP can cover a similar area. This emphasizes the significant aspect of an EMP from a high altitude burst that the large amplitude fields can cover large geographical regions. The outgoing gammas from the burst form a spherical shell which expands with the velocity of light. Since most of the gammas are emitted in about 10 nanoseconds, the thickness of the shell at any instant is a few meters. When the gamma shell begins to intersect the absorbing layer of the atmosphere, an outgoing electromagnetic pulse is generated. This pulse moves along with the remaining gammas. Above about 40 kilometers altitude, the atmospheric density is sufficiently small that the high energy gammas are not affected appreciably. The atmospheric density is large enough that the gammas are absorbed by Compton scattering below 40 kilometers. The gamma absorption is nearly complete by the time they reach 20 kilometers altitude. The source region for a high altitude burst is thus between about 20 to 40 kilometers, which is approximately 65,000 to 130,000 feet. At the altitude of the source region, the stopping range of Compton recoil electrons is of the order of 100 meters. In traveling this distance, the Compton electrons are strongly deflected by the geomagnetic field with a gyro radius of about 100 meters. The Compton recoil current, therefore, has strong components in directions transverse to the gamma propagation direction. This transverse current radiates an electromagnetic wave that propagates in the forward direction. The outgoing wave keeps up with the gamma shell and is continually augmented by the transverse Compton current until the gammas are all absorbed. Then the electromagnetic wave goes on alone as a free wave or pulse. Secondary electrons produced by the Comptons make the air conducting. This conductivity attenuates the electromagnetic pulse. The amplitude of EMP is determined by a balance between:

EMP FROM HIGH ALTITUDE BURSTS
EXAMPLE OF GEOMETRY BEING CONDENSED



h= HEIGHT OF BURST = 400 km = 250 MILES

s= DISTANCE TO HORIZON = 2,250 km = 1,400 MILES

A HIGH ALTITUDE BURST ILLUMINATES LARGE GEOGRAPHICAL REGIONS WITH GAMMA RAYS.

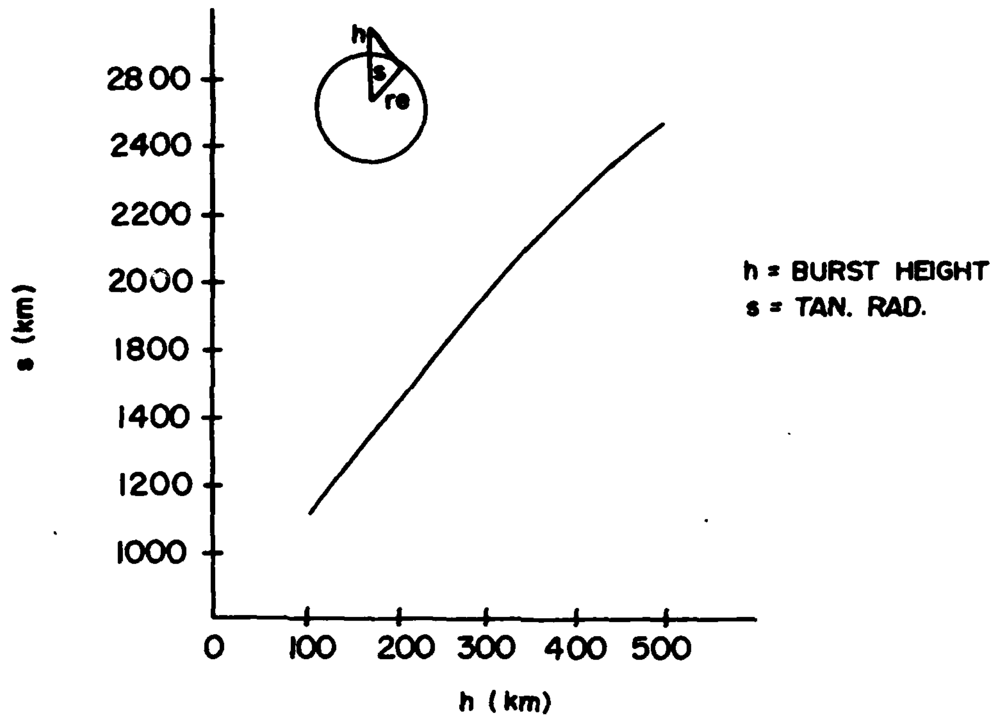
FIGURE 5

a. Increase due to transverse Compton current.

b. Attenuation due to conductivity.

5. SUMMARY OF EMP GENERATION. Gamma rays are scattered from molecules with the emission of Compton electrons in the forward direction with energies on the order of 1/2 million electron volts. The motion of the Compton electrons is modified by the geomagnetic field. They follow a spiral path about the magnetic field lines until they are stopped by collisions with atmospheric molecules. As the Compton electrons collide with atmospheric molecules, further ionization occurs and the conductivity increases. The propagation of the EMP depends on the conductivity of the region through which it passes. Dispersion, attenuation, and reflection may occur. The circular component of the Compton electrons represents a magnetic polarization, and the linear component represents an electric polarization. Both the magnetic and electric polarizations vary with time and, consequently, can radiate electromagnetic energy. This can also be viewed as a collective flow of electrons along the field which radiates in the transversal direction. Compton electrons that move parallel to the geomagnetic field are not deflected. Thus, the EMP amplitude is small in two directions along the geomagnetic field line passing through the burst point. The EMP amplitude is a maximum on those rays from the burst point which run perpendicular to the geomagnetic field in the source region. Since the location of enemy bursts cannot be predicted in relation to a system, one should harden for the worst case. Once again, the significance of the large geographical areas that high altitude EMP can cover needs to be emphasized. The geographical coverage as a function of the height of burst can be obtained by considering the tangent radius. The tangent radius is the arc length between the line from the earth's center to the burst point and the line from the earth's center to the point where a line from the burst point is tangent to the surface of the earth. See Figure 6. For a burst at 300 kilometers, the tangent radius is 1920 kilometers, or about 1200 miles. The EMP from the burst can cover this region.

6. EMP EFFECTS. Most of the damage caused by the EMP threat occurs due to fairly simple effects. The strong electromagnetic fields are converted into large voltages and currents on any power lines, towers, cables, conducting loops, etc. These large currents and voltages, which rise



TANGENT RADIUS FOR A HIGH ALTITUDE BURST
FIGURE 6

very rapidly, can destroy sensitive components and open protective relays, thereby requiring repair, start-up, etc. Semi-conductor devices are particularly sensitive to voltage and current surges. The strong fields associated with EMP may destroy magnetic memory, cause logic circuits to be randomly disarranged (thereby destroying computer or other electronic device results at least temporarily) and cause all sorts of similar results. EMP also produces severe distortion and disturbance of radar and communications systems, at least during the pulse itself. The degree of permanent damage, if any, depends upon such factors as frequency range, bandwidth, antenna size and orientation, and the types of components involved. Protection against this EMP threat thus involves several facets, each of which is addressed further in this handbook. The effects of EMP may range all the way from temporary interference, as with a communications channel or a computer in which a sequence of calculations are caused to be in error, to permanent damage, as would result if a semi-conductor or rectifier is burned out. Other intermediate effects such as computer memory destruction, requiring reprogramming and/or reinitialization, or interruption, requiring system recycling to become operational, are also possible.

6.1 Electric Field Effects. Examples of the electric field pulse generated by a high altitude burst will be given for the case where the line from the center of the earth to the burst point makes a relatively small angle with the geomagnetic field in the source region. This would be the case for a burst at mid-to-high latitudes. The result is that the electric field at ground zero is relatively small compared to the field at the maximum field point (where a line from the burst point to the maximum field point is orthogonal to the geomagnetic field lines in the source region).

The average distance in air at sea level that a gamma ray travels before making a Compton collision is about 200 meters. A few gammas go as far as a few kilometers. Compton electrons travel outwards only a meter or two before being stopped by air. The radial current of Compton electrons is very intense near burst and decreases with radius. This current becomes negligible at a few kilometers. The source region for a surface burst is thus more dependent on the absorption of gammas in the atmosphere than on the yield of the weapon. Each of the Compton electrons in slowing down make many thousands of secondary electrons.

Thus, air becomes conducting. The outward displacement of electrons in air results in a radial electric field.- This radial electric field drives a conduction current which tends to cancel the Compton current and thereby limits the electric field. The ground shorts out the radial electric field near it since the ground is normally a better conductor than air. Near the ground, conduction electrons find an easier path by flowing down to the ground and back towards burst point. The result is a current loop which generates an azimuthal magnetic field. A vertical electric field is required in connection with the vertical component of conduction current. This vertical electric field can be regarded as connecting Compton electrons in the air with their image charges in the ground. Thus, for a surface burst, there is a radial and vertical electric field and an azimuthal magnetic field. Irregularities in ground properties and surface features give other components. The magnitude of the fields depend strongly on distance from the burst and on the yield. Thus, EMP hardness specifications will depend strongly on the general level of attack to which it is desired that the system survive. Hardness to other weapons effects, like blast, should be balanced with EMP hardness.

6.2 EMP Effects Below Ground. The EMP fields below the ground must also be considered. Electromagnetic fields diffuse into the ground. The penetration depth depends on ground conductivity and frequency component considered. A greater ground conductivity leads to a smaller penetration depth. The high-frequency components penetrate less deeply than the low-frequency components of the pulse. The source region where Compton current and air conductivity are important is a few kilometers in radius. Outside this region, the fields propagate like radio waves and fall off with the reciprocal of distance. From a large distance, the source region looks like a conducting hemisphere that is charged suddenly and then rings and radiates.

D. EMP PROTECTION

1. INTRODUCTION. For the design of a particular facility, first the threat level, the survivability requirement, and the susceptibility level of the systems must be determined. The operational and functional requirements of the facility must also be considered; i.e., the design of EMP protection for a facility which must continue to operate during a nuclear detonation and for an extended period post-blast may be vastly different from that of a facility that needs only to be able to survive the nuclear blast and to operate for a short period post-blast. The level of threat and the frequency band over which the threat exists depends on the weapon size, burst distance from the system, altitude, and several other factors. The values assumed for these parameters will depend on the mission survival requirements established. A guideline for threat level would be the overpressure that the building can withstand and the EMP anticipated from a burst yielding this overpressure. To say a system is to survive the EMP for a given threat level is *definite only* if the system and the threat level are definite. EMP can exist independently of blast if the burst occurs at a distance or at high altitudes, so protection may be required even for unhardened facilities many miles away from probable targets. The amount of hardening required must be determined during design stages based on the above factors since the state-of-the-art is such that "cookbook" approaches are not possible and the approach used should be selected on the basis of each individual system. In the case of a high-altitude detonation, high energy waveforms, but somewhat less intense than those which appear in the ionized sphere, are radiated from the source region. Various responses of surface equipment to this EMP can be observed, ranging from inconsequential "static" to burnout. The most severe effects are associated with the more susceptible components which are connected to long exposed cables or antennas. One candidate for a severe effect would be a transistorized shortwave receiver connected to a large antenna.

2. EMP PROTECTION PHILOSOPHY (General). EMP protection philosophy is based on protection from three environmental areas of concern: ground current effects, magnetic field effects, and electric field effects. The solution to the

problem of ground current is to control the path of current which is collected by water pipe, conduit, or other conductive materials entering a facility or a structure, without creating objectionable electric fields due to discontinuities or penetrations of such conductors. Ground currents entering the vicinity of a structure through conductive materials are conducted around the structure through a ground counterpoise or structure shield and are dissipated into the earth or other conductive materials on the opposite side of the structure. If water pipes or conduits are allowed to enter a structure without being connected to the ground counterpoise, or other paths around the structure, the ground currents would be conducted throughout the structure, causing unwanted electromagnetic fields to be present in and near the structure. In order to prevent the possibility of malfunction due to circulating currents in neutral wiring of transformers, such a system neutral, if grounded, shall be grounded at only one point IAW existing electrical codes (i.e., National Electrical Code). To protect electrical wiring and components from magnetic and electric fields, some type of shield must be utilized. The shield must surround items to be protected. This type of protection does not completely isolate the item from the electromagnetic field but attenuates the field strength to an acceptable level. Conductors may be shielded with some form of raceway, or conductor shields and cable armor. Components may be shielded with sheet steel housings. An entire structure housing electrical system may be shielded with sheet steel or nominal reinforcing bars when properly bonded and grounded. However, the use of reinforcing bars for shielding is not very efficient and, except for cases where only a low level of attenuation is needed, the amount of protection realized by this method is generally insufficient and additional shielding will be required. The cost to shield by reinforcing bars, when compared to the cost of overall shielding for a given attenuation, is generally more expensive and, therefore, unwarranted. Shielding against magnetic field pulses consists of enclosing the region to be protected within an electrically conductive shield. The magnetic pulse flux tends to concentrate initially on the outside of the enclosing shell, progressively penetrating toward the inside of the shell as the pulsed field encompasses it. If the shell is electrically continuous, the voltage induced by the pulse field forces a current around the shell. The intensity of the voltage and current surges produced by EMP must be reduced or attenuated to a level that will not damage or cause malfunction in the system being protected. This is accomplished

chiefly by reflecting the incident fields from the shielded envelope protecting the area, and by exponential absorption of the residual currents induced in the protective shielding. These two basic methods of achieving attenuation may reduce the EMP to an acceptable level in some instances.

a. Reflection. The reinforcing bars, wire mesh and/or sheet metal housing utilized to protect the facility systems will reflect some of the incident EMP fields. Electric fields are reflected more than magnetic fields because of the greater difference in the wave impedance between electric fields and the inherently low intrinsic impedance of metals. That which is not reflected induces a current in the shield and is exponentially absorbed in the metal.

b. Absorption. Absorption is the principal method used to attenuate EMP. As the impinging field is strongly magnetic, thus a low impedance source, little energy is reflected from the shield. This causes large residual currents, eddy currents, to remain on the shield. The eddy currents interaction with the shield absorbs some of the field energy and dissipates it in the form of heat.

Consistent with past experience in radio frequency interference and electromagnetic hazards to ordinance problems, the EMP hardness should be considered during preliminary system design and layout. EMP hardening requirements should then be kept clearly before the engineers during advanced design and system development stages. If the EMP problem is not approached until late in system design, the cost and weight penalty can be enormous. One accepted approach is to incorporate as many of the simple EMP protective measures as possible early in the design phase. The basis for this approach is that (with certain exceptions) the costs for various protective techniques are generally small, provided that they are incorporated in an early phase. Such low cost features include the use of clipping circuits to protect sensitive transistors or the selection of noise-immune cable and grounding systems, which employ balanced twisted pair cables in shielded conduit. If some shielding is required, little extra cost is incurred to provide shielding against the most severe threat, since the electromagnetic performance requirements is only one of the determining factors of how the system is designed and constructed. In most shielding situations, mechanical fabrication and corrosion protection costs predominate. The shielding, therefore, can be conveniently

overdesigned. Thus, it is considered more economical to include additional EMP protective features rather than to risk rejection of the entire system during final EMP test acceptance procedures. This viewpoint is reinforced because of the uncertainties involved with a number of practical considerations such as corrosion of joints, method of installation, and later modifications.

2.1 Application to Existing Facilities (General).

a. Planning. Where costs are not prohibitive, it will be desirable to apply EMP protective measures to existing communications facilities, personnel shelters, or otherwise nuclear hardened buildings. Many present structures were built before the existence of an EMP threat had been realized. In the design of protective measures for such a large variety of structures, consideration of the following items should be very important to the designer providing EMP hardening for the structure.

(1) Threat Levels. The expected EMP threat levels at the structure are based on type of burst, distance to burst, and weapon yield. A guideline as to weapon yield and anticipated distance from a burst would be the overpressures that the building has been designed to withstand.

(2) Susceptibility. A limited amount of susceptibility data is given in this document. Existing EMP handbooks and test reports are continuously being published providing more information on susceptibility data. In general, only engineering estimates of system susceptibilities are known at this time. Some components of systems are known to be more susceptible than others based on inherent voltage and current characteristics. Discussion of general susceptibilities of some types of components which are common to a large number of systems are given. Power susceptibility of some components such as motors, relays, transformers, or switches have been measured.

(3) Cost of Retrofits. The level of funding available as compared to the cost of the anticipated protective measures may predominate in the determination of the extent of the EMP retrofit program. In some cases, it may be more economical to abandon a site and rebuild with plans which include design of protective measures.

b. Examination of Plans. A preliminary step in the program to EMP harden existing facilities is to examine available construction drawings and make a determination of the construction methods used at the site. For example, if the construction is typically reinforced concrete, determine the diameter, spacing or extent of use of rebar and, if any portion of the rebar was welded or brazed at joints and intersections. A limited amount of shielding from radiated fields will be provided by having bonded reinforcing steel as part of the basic structure.

c. Site Survey. After an initial examination of construction drawings and plans, it will be advisable to make a visual inspection of the facility; compare construction to as-built drawings if available.

(1) Shielding. Any continuous steel plates will also provide shielding and should be considered as part of the EMP protection inherent in the structure. The use of additional shielding such as form fitted copper sheeting, welded steel lining, or built-in place commercial shielded enclosures should also be considered.

(2) Grounding. Determination of the availability and quality of the grounding system for impulses and surges would be the next step in a retrofit program. Existence of ground connections to the basic structural steel and reinforcement steel should be determined through resistance measurement. These grounds can be supplemented by adding an appropriately designed impulse ground counterpoise system to obtain surge grounds with resistances on the order of about 10 ohms. Measurement of soil resistivity will aid in designing additional grounding.

(3) Commercial Utility Lines. It is usually anticipated that commercial utility lines will be destroyed and so a transfer switch will normally be available to switch the load to the emergency power system. This transfer switch must be protected from damage from the initial EMP encountered. A standard lightning arrester at the transfer switch is normally sufficient for this purpose if connection to a low impulse impedance ground is available near the transfer switch and the switch is on the high voltage side of a step down transformer. Typically, the nearest existing lightning arrester will be on the last overhead transmission line pole. The site survey should locate and evaluate the quality of existing arresters, transfer switch grounds and distribution transformers.

(4) Emergency Power. Vulnerable points of the emergency power system which require protective measures should be determined during the survey. These include remote control conductors, remote indicator wiring, generator exciter control, and battery charging circuits. All such conductors should be contained in ferrous conduit with threaded couplings. Power distribution from the generator must be similarly contained in ferrous conduits. Entries of this conduit into switches and junction boxes near the generator should be suited for application of radio frequency gaskets or electrically conductive bonds.

(5) Internal Power and Control Wiring. The means of distribution of power conductors and control conductors within the facility should be determined by examination of the construction drawings and visual inspection of the installation. The type of conduit used is important. Rigid ferrous conduit with threaded couplings can provide shielding of conductors while condulets give considerably less protection and will require additional measures, such as the application of conductive filter-loaded plastic resins to each joint connection. Numerous bends in conduit runs tend to degrade the shielding provided. The larger the conduit diameter, the more effective it will be. Multiple runs of conductors within cable trays tend to provide limited shielding for each other. In the survey, such multiple cable runs should be examined for the possibility of installing them within enclosed ferrous raceways. Entries of conduit into switch boxes and junction boxes should be inspected for continuity, tightness, and quality of couplings. Box lids will require installation of radio frequency gaskets with appropriate treatment of the mating flanges with conductive coatings. Open indicator panels and control racks may require enclosure of wiring within an integral metal cabinet, and the results of the survey should indicate the quality of existing panels, openings, and seals, as well as existing potential for added shielding measures.

(6) Signal and Telephone Lines. Overvoltage protection measures should be applied at the point where the lines first penetrate the shelter wall. All incoming lines (this includes power, telephone, and data lines) should be rerouted so that at the entry point, protectors can be physically mounted on a bulkhead which, in turn, can be electrically connected directly as possible to an impulse grounding system.

(7) Antenna Lead-in Cables. Antenna masts and cables should be examined for the existence of previously installed lightning protection measures.

3. ENERGY COLLECTION. The radiated electromagnetic fields from a high altitude nuclear detonation are important since these fields can appear over large regions. These fields can cause charges to flow on any good conductor. The way in which the energy is collected is often complex; but, in general, the larger or more extensive the conductor, the greater the amount of energy collected. For example, the whip antenna of an automobile radio will collect far less energy than an AM broadcast transmitting antenna. Typical collectors of EMP energy include:

a. Long cable runs, piping, or conduit.

b. Large antennas, antenna feed cables, metallic guy wires, or metallic antenna support towers.

c. Power or telephone lines.

d. Metallic structural building members such as girders, corrugated metal roofs, expanded metal lathe, or rebars.

e. Buried pipes or cables.

f. Long runs of electrical house or building wiring, conduit, etc.

g. Metallic fencing, railroad tracks.

4. RESPONSE OF COMPONENTS. The energy appearing in the electromagnetic environment is converted, often in a complex fashion, into large amplitude currents and voltages flowing on any metallic conductor. To cause damage, it is necessary that these currents and voltages encounter a sensitive component such as a transistor. In the case of an antenna, this would be the normal consequance of the function or purpose of the antenna. In the case of other metallic structures, various obscure details (such as quality of welds) control the distribution of currents and voltages. Electrical systems exposed to EMP may suffer degradation in two distinct ways: (1) functional damage or (2) operational upset. If sufficiently large electric transients are introduced, a component or a subsystem may become permanently inoperative until some part or parts are replaced. If a system is permanently damaged in this manner, it is

said to have suffered functional damage. Other types of functional damage may occur wherein a particular device or subsystem is rendered only partially capable of executing its entire range of functions. Another aspect of functional damage is the decrease in the lifetime of a particular component or subsystem. Electrical transients may temporarily impair the performance of a system. This impairment may last for only a few microseconds or could be hours. This temporary impairment of the system's operation is known as operational upset. The importance of either functional damage or operational upset within the system depends upon the specific characteristics of the system. Beginning with these definitions of degradation, it is useful to consider examples of each type of effect. Burnout of a transistor or the opening of a fuse are clearly two examples of functional damage. Examples of operational upset are the erasures of magnetic core memories of computer systems or the resetting of flip-flop circuits. Depending on system design, the unanticipated change of circuit conditions or temporary malfunctioning of a number of control devices could range from insignificant to catastrophic. Electronic components are often very sensitive to functional damage or burnout. These are listed in the order of decreasing sensitivity to damage effects:

a. Magnetic core memories (erasures).

b. Microwave semi-conductor diodes.

c. Field-effect transistors.

d. Radio-frequency transistors.

e. Audio transistors.

f. Silicon-controlled rectifiers.

g. Power rectifier semi-conductor diodes.

h. Vacuum tubes.

Thus, systems employing vacuum tubes are far less susceptible to EMP effect than those employing transistors. Various electronic or electrical systems are subject to malfunction:

a. Most Susceptible:

(1) Low power, high-speed digital computer (upset) either transistorized or vacuum tube.

(2) Systems employing transistors or semi-conductor rectifiers (either silicon or selenium), such as:

(a) Computers.

(b) Computer power supplies.

(c) Transistorized power supplies.

(d) Semi-conductor components terminating long cable runs, especially between sites.

(e) Alarm systems.

(f) Intercom systems.

(g) Life-support system controls.

(h) Some telephone equipment which is partially transistorized.

(i) Transistorized receivers.

(j) Transistorized transmitters.

(k) Transistorized 60 to 400 cps converters.

(l) Transistorized process control systems.

(m) Power system controls.

(n) Communication links.

b. Less Susceptible:

(1) All vacuum tube equipment (does not include equipment with semi-conductor or selenium rectifiers):

(a) Transmitters.

(b) Receivers.

(c) Alarm systems.

(d) Intercoms.

(e) Teletype-telephones.

(f) Power supplies.

(2) Equipment employing low current switches, relays, or meters:

(a) Alarms.

(b) Life support systems.

(c) Power system control panels.

(d) Panel indicators, status boards.

(e) Process controls.

(3) Hazardous equipment containing:

(a) Detonators.

(b) Squibs.

(c) Pyrotechnical devices.

(d) Explosive mixtures.

(e) Rocket fuels.

(4) Other long power cable runs employing dielectric insulation, equipment associated with high energy storage capacitors or inductors.

c. Least Susceptible:

(1) High voltage 60 Hz equipment:

(a) Transformers.

(b) Motors.

(c) Lamps.

(d) Filament.

(e) Heaters.

(f) Rotary converters.

(g) Heavy duty relays.

(h) Circuit breakers.

(i) Air insulated power cable runs.

The less susceptible equipment or components would be made more susceptible if they were connected to long exposed cable runs, such as intersite wiring or overhead exposed power or telephone cables.

5. DESIGN PRACTICES. In previous sections, a discussion of EMP generation and effects, general protection philosophy and general response of components was presented which was intended to give the reader a basic understanding of EMP and the magnitude of providing adequate EMP protection. The rest of this handbook will concentrate on providing a basic design practice for EMP. The information is basic in nature and only highlights major areas that need to be considered in basic EMP protection. Much of the information in this section was obtained from a DNA Awareness Course on EMP and provides a good starting point for considering EMP protection. This section will emphasize systems engineering from the start and considers the entire system design first and then breaks up into individual component design.

5.1 Systems Aspects. Perhaps the most disconcerting feature of most system EMP programs is the magnitude of a hardware assessment. Some loose physical criteria need to be applied early, in order to guide the sorting and the choosing. As is often the case in such situations, the first steps may be partly artificial. To start with, the zoning approach in structuring a system and its EMP analysis will be considered. Before starting though, various system definitions should be introduced.

5.1.1 System Level Concepts and Definitions. It is important to keep in mind that when we say "system", this can encompass a broad spectrum of configurations in size, shape, and complexity. A pocket transceiver is as much a "system" as is an ABM radar site. Thus, its definition is: a complete, self-contained primary-mission entity. Some other system-level concepts and definitions are noted here:

a. Zoning: The identification and integrations of regions of similar electromagnetic (EM) environment and/or susceptibility.

b. Clustering: The grouping of elements of similar characteristics and purposes.

c. Layering: The sequencing of zones and protective measures between outer environment and inner equipment.

d. Damping: The use of lossy elements or materials to absorb EM energy.

e. Violations: The features which represent defects from a systems hardness viewpoint.

f. Fixes: Obviously, the measures taken to rectify violations.

5.1.1.1 Zoning. Considerations of EM zones within a system nearly always appear overtly in terms of shielding effectiveness. Zone boundaries are generally constrained to coincide with major geometric or structural contours, or with intentionally introduced shields or shielding enclosures. Thus, it is usually the case that zoning considerations do not appear explicitly in an EMP systems analysis. However, there have been system cases in which the EM geometries were so intricate that elementary shielding considerations were obviously inadequate. It was then essential to perform a meticulous mapping of the EM zones. This has been particularly true in certain nuclear test situations.

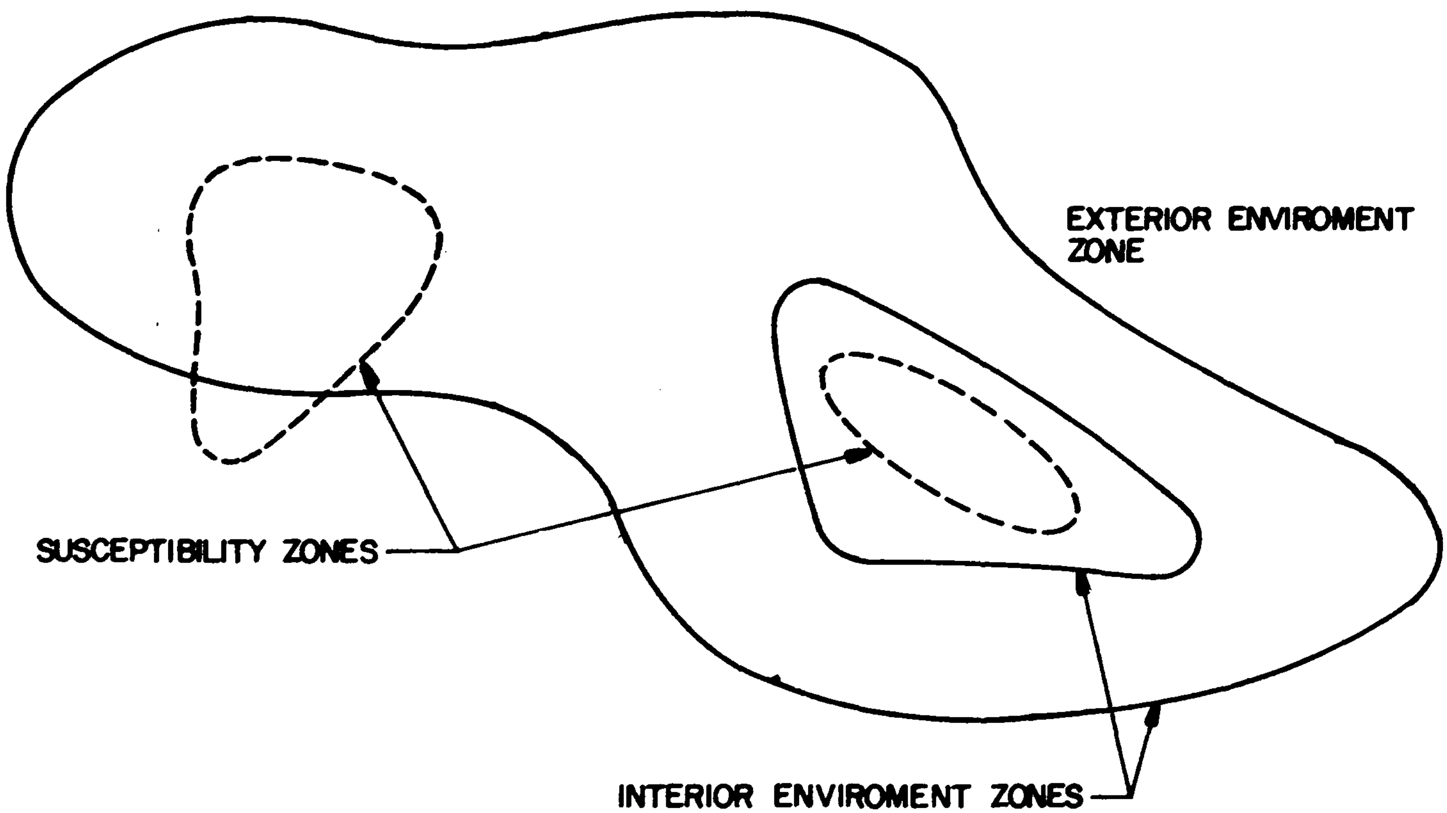
a. Zoning Approaches. Electromagnetic (EM) zones may be defined in two broad ways:

(1) Environmental zoning, in which the magnitude and shape of the field pulse is defined within the successive regions from outside in.

(2) Susceptibility zoning, in which the magnitude and frequency (or time) domains corresponding to the vulnerability thresholds are scaled from inside out.

In a "good" system (See Figure 7), zone boundaries appear as (more-or-less) concentric iso-contours and there is an appropriate coincidence between environmental and susceptibility zones.

ZONING APPROACHES



TYPICAL MAPPING OF ZONING APPROACHES
FIGURE 7

b. Zone Definition. It is common practice to define the levels of different zones in terms of relative dB. Physical features (such as walls, cabinets, etc) with which zone boundaries are most usually associated, generally appear to be good for 20-30 dB, without specific EMP-oriented treatment. Zones can also be delineated in terms of other electromagnetic interaction specifications. For example, equipment tested to meet FED STD 461/462 or FED STD 222-A belong in one of the better shielded zones.

5.1.1.2 Clustering. Evidently, one of the things which should improve EMP hardness is the reduction of the area over which vulnerable elements are located. All other systems aspects being equal, it is generally best to contour the EMP zones as compactly as possible. This is especially important if upset, such as computer memory erasure, is concerned.

5.1.1.3 Layering. Most of our simple examples here show EMP protection as appearing in several successive geometric stages or layers. Of course, each boundary has to be complete in the sense that apertures and penetrations must be treated to preserve what was gained at that layer (remember the weakest link). There seems to be a tendency to deal with EMP at one (or at most, two) boundaries. In some sense, EMP tends to be seen like "plant security". Put up one good, well-patrolled fence. But, in many EMP cases, this is quite unrealistic. For instance, in a deeply buried system, it is plainly obvious that some protection can be gained almost "free" from the earth cover itself. It is also unrealistic in "porous" systems -- that is, systems with very many apertures and penetrations.

5.1.1.4 Ringing. There are two wholesale approaches to EM field protection. One of these is the "iron curtain" method, in which the various elements are thoroughly shielded and electrically isolated from one another. The other is the "common sink" in which the various elements are massively connected together. The difficulty is that one really cannot do either thing thoroughly. Elements must be connected together somehow, but they cannot all be placed in intimate contact. So, the result is something in between, which often ends up acting like a high-Q EM cavity, or LC circuit. This is basically why many partially shielded systems exhibit strong ringing when excited by means of an EMP stimulator.

5.1.1.5 Damping. Such ringing represents efficient storage of EM energy and a prolongation of the time during which it can be coupled to internal elements and circuits. We can reduce this condition by spoiling the Q of the enclosures and implicit circuits. The concept is primitively illustrated here in the insertion of (parallel) damping resistors. (Series damping requires careful circuit analysis to avoid making matters worse.) This technique has been very successful in some types of nuclear test interference problems. Most shielding systems have characteristic impedances in the range of 5 to 200 ohms. Damping resistors of corresponding value are used; the exact choice is not critical. This technique is most appropriate wherein the shielded enclosure is (for a variety of reasons) poor, thus permitting entry of the higher frequency (ringing-frequency) components.

5.1.1.6 Violations and Fixes. The zoning concept has another advantage in complicated system evaluations. It permits the definition of specific locations and components (along a boundary) requiring EMP treatment. In the strictest analytic sense, one assigns a minimum dB margin which all points and elements within and at such a boundary are to satisfy. Those that don't are at once identified as "violations". As we said before, "fixes" clearly encompass those measures taken to redress these situations, or in some cases, to redress their consequences. Violations generally fall in one of four broad classes as outlined here. The subsequent hardware categories are addressed to rectify one or another of these general conditions:

a. Circuit Considerations.

b. Shielding.

c. Cooling.

d. Grounds.

e. Protection and Testing.

5.1.1.6.1 Circuit Considerations. Extensive studies have been made on evaluating the effect of EMP energy in electronic circuits and components. Chapter 5 of reference 27, EMP Handbook for Missiles and Aircraft, provides additional information on component vulnerability and should be consulted for further information. One of the main concerns, however, is how EMP energy gets into circuits. One method

is coupling. Coupling should be avoided in circuit layouts - most notably, inductive loops. Good circuit layout practices apply to large cable systems or to printed circuit package. Another is by injection as extraneous voltage or current pulses at peripheral terminals. To solve these problems involves detailed circuit analysis techniques and special computer programs, and it is felt that further discussion in this area is beyond the scope of this basic handbook. References 22 and 27 should be consulted for further information.

5.2 Shielding. For comparative purposes, it has become customary to rate a design or product in terms of "shielding effectiveness", measured in dB. This is a somewhat ambiguous term since it will depend, in practice, on the size of the box, the location of the item, the frequency domain and the method of measurement. Basically, it can be viewed as a measure of a certain internal environment "with" versus "without" the protective scheme.

5.2.1 How Do EMP Shields Work? In the EMP frequency domain, a dominant mechanism in shielding effectiveness is inside cancellation or field reflection due to induced surface currents as illustrated here. Thin walls, high resistance paths, apertures, seams, etc., seriously affect the reflection or cancellation characteristics and serve as internal field generators as well. See Figure 8 for typical shielding design problems. A good shield must, therefore, be sufficiently thick, continuous, complete, and tight. This is essential for shielding above 60 dB.

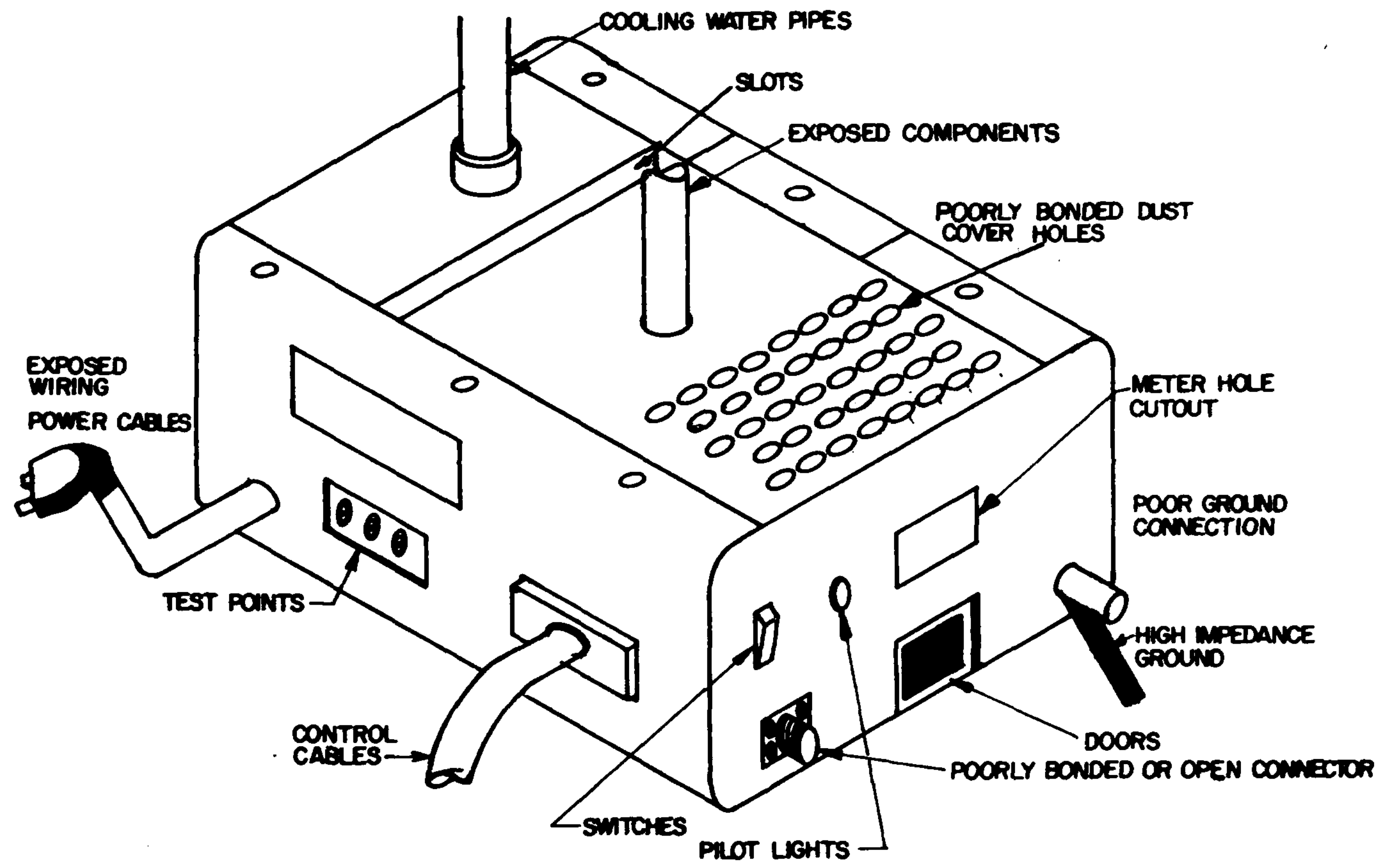
5.2.2 Ideal Versus Realistic Shielding. Of course, mechanical and electrical inputs and outputs are also essential, and economic realities place real limits on wall thickness. Shielding hardware considerations generally boil down to compromises in relation to:

a. Wall thickness and material.

b. Apertures -- tightness.

c. Penetrations -- conductors.

5.2.3 Shielding Effectiveness. The plane wave theory (or transmission line theory) of shielding is the basis of the most commonly used shielding design data. The resulting set of design equations is based upon the separation of the shielding effectiveness into three additive terms: absorption



TYPICAL SHIELDING DESIGN PROBLEMS
FIGURE 8

loss, reflection loss, and a correction term to account for re-reflections within the shield.

The shielding effectiveness (in decibels) of a large, plane sheet of metal with an EM wave arriving along a path perpendicular to the sheet has been shown to be:

$$SE = \underset{A}{20 \log|e^{\gamma \ell}|} + \underset{R}{20 \log|\tfrac{1}{\tau}|} + \underset{C}{20 \log|1 - \Gamma e^{2\gamma \ell}|}, \quad (1)$$

where: ℓ = thickness of the shield.
γ = propagation constant of the shield.
τ = transmission coefficient, and
Γ = reflection coefficient.

The shielding equation is often written as:

$$SE = A + R + C \quad [2]$$

where A, R, and C are the indicated three terms in Equation 1 and represent, respectively, the Absorption Loss, the Reflection Loss, and the Correction Term for re-reflections as discussed earlier. In a particular shielding application, the values of the constants γ, Γ, and τ depend upon the conductivity (σ), permeability (μ), and permittivity (ε) of the shielding material. The values of Γ and τ depend also upon the wave impedance of the EM wave impinging upon the shield. For convenience in the use of the shielding effectiveness equation, the individual terms A, R, and C have been expressed in more readily usable forms as functions of the EM wave's frequency (f) and of the shield's thickness (ℓ), relative permeability (μ_r), and conductivity relative to copper (g_r). Simplified approximate expressions have been derived for the reflection and correction terms. The selection of the appropriate approximate expression will depend upon whether the wave impedance is low (Z_w<<377Ω; magnetic field), medium (Z_w≈377Ω; plane wave), or high (Z_w>>377Ω; electric field). Low impedance fields are found in the proximity of loop antennas, high impedance fields are found near dipole antennas, and plane waves exist away from the near fields of source antennas.

5.2.3.1 Absorption Loss. The absorption loss of an EM wave passing through a shield of thickness ℓ can be shown to be given by:

$$A = K_1 \ell \sqrt{f \mu_r g_r}, \text{ (dB)} \quad (3)$$

where: K_1 = 131.4 if ℓ is expressed in meters, or 3.34 if ℓ is expressed in inches.
f = wave frequency, Hz.
ℓ = shield thickness
μ_r = relative permeability of shield material, and
g_r = conductivity of shield material relative to copper

Note that the absorption loss (in decibels) is proportional to the thickness of the shield and also that it increases with the square root of the frequency of the EM wave to be shielded against. As to the selection of the shielding material, the absorption loss is seen to increase with the square root of the product of the relative permeability and conductivity (relative to copper) of the shield material.

Table 1 contains a tabulation of electrical properties of shielding materials (g_r and μ_r); since μ_r is frequency dependent for magnetic materials, it is given for a typical shielding frequency of 150 kHz. The last two columns of Table 1 evaluate Equation 1 to give the absorption loss at 150 kHz for both a one millimeter and a one mil (.001 inch) thick sheet for each of the listed materials. The absorption loss for other thicknesses can be calculated by simply multiplying by the shield thickness in millimeters or mils. Shield thicknesses are commonly expressed in either millimeters (mm) or milli-inches (mils); these two units are related as follows:

1 mm = 39.37 mils or 1 mil = .0254 mm.

The variation of absorption loss with frequency, as well as a comparison of the absorption loss of three common shielding materials one mm thick, can be seen in Table 2. Also included is a listing of the relative permeability, as a function of frequency, for iron.

Remember that the absorption loss is just one of three additive terms which combine to give the attenuation (shielding efficiency) of the shield. At this point, the absorption loss has been presented in equation form (Equation 3) and tabular form (Tables 1 and 2). The tabular forms are easy-to-use sources of accurate results when the shield material and frequency of interest are included in those tables and graphs. Quick results for almost any material and frequency combination can be obtained from an absorption nomograph, but the results

are generally less precise; nomographs are a good source of data for initial design purposes. Once a shielding material and thickness are tentatively selected, one may wish to compute a more precise value of the absorption loss by evaluation of Equation 3.

5.2.3.2 Reflection Loss. According to Equation 1, the reflection loss portion, R, of the shielding effectiveness, SE, is given by:

$$R = -20 \log |\tau| \text{ dB} \qquad [4]$$

Where: τ is the transmission coefficient for the shield. The reflection loss includes the reflections at both surfaces of the shield and is dependent upon the wave impedance and frequency of the impinging EM wave as well as upon the electrical parameters of the shielding material. It is independent of the thickness of the shield.

In a manner analogous to the classical equations describing reflections in transmission lines, the shield reflection loss can be expressed as:

$$R = 20 \log \frac{|1 + S/2|}{|4S|} \text{ dB} \qquad [5]$$

where: S is defined as the ratio of the wave impedance to the shield's intrinsic impedance and is analogous to the voltage standing wave ratio in transmission line practice. While the shield's intrinsic impedance is easily determined from the electrical properties of the shield material, the wave impedance is highly dependent upon the type and location of the EM wave source.

5.2.4 A Shield is a Magnetic Field Reducer. Let us neglect apertures and penetrations, so that the internal field inside a shield is determined by overall field penetration or "diffusion". Assume further that the incident field is more-or-less "white" in frequency content, as for EMP. Then the internal waveform will tend to be dominated by frequencies just below the attenuation cutoff, and, of course, this effect would be accentuated in internal magnetic field.

5.2.5 Diffusion Shielding. There is another kind of shield -- the semi-permeable type. Examples: earth cover, rebar grids. Here the effective skin depths may be large, and the total attenuation relatively small -- like 30 dB.

TABLE 1

ELECTRICAL PROPERTIES OF SHIELDING MATERIALS AT 150 KHZ

Metal	Relative Conductivity g_r	Relative Permeability μ_r	Absorption Loss (dB) 1 mm thick	1 mil thick
Silver	1.05	1	51.96	1.32
Copper, annealed	1.00	1	50.91	1.29
Copper, hard-drawn	0.97	1	49.61	1.26
Gold	0.70	1	42.52	1.08
Aluminum	0.61	1	39.76	1.01
Magnesium	0.38	1	31.10	.79
Zinc	0.29	1	27.56	.70
Brass	0.26	1	25.98	.66
Cadmium	0.23	1	24 41	.62
Nickel	0.20	1	22.83	.58
Phosphor-bronze	0.18	1	21.65	.55
Iron	0.17	1,000	665.40	16.90
Tin	0.15	1	19 69	.50
Steel, SAE 1045	0.10	1,000	509.10	12.90
Beryllium	0.10	1	16.14	.41
Hypernick	0.06	80,000	484.00*	88.50*
Monel	0.04	1	10.24	.26
Mu-metal	0.03	80,000	2488.00*	63.20*
Permalloy	0.03	80,000	2488.00*	63.20*
Steel, stainless	0.02	1,000	244.40	5.70

*With no saturation by incident field.

TABLE 2

ABSORPTION LOSS, A, OF 1 MM METAL SHEET

Frequency	Iron		Copper		Aluminum	
	μ_r	A (dB)	μ_r	A (dB)	μ_r	A (dB)
60.0 Hz	1,000	13	1	1	1	0.8
1.0 kHz	1,000	54	1	4	1	3.0
10.0 kHz	1,000	171	1	13	1	10.0
150.0 kHz	1,000	663	1	56	1	40.0
1.0 MHz	700	1,430	1	131	1	103.0
3.0 MHz	600	2,300	1	228	1	178.0
10.0 MHz	500	3,830	1	416	1	325.0
15.0 MHz	400	4,200	1	509	1	397.0
100.0 MHz	100	5,420	1	1,310	1	1,030.0
1.0 GHz	50	12,110	1	4,160	1	3,250.0
1.5 GHz	10	6,640	1	5,090	1	3,970.0
10.0 GHZ	1	5,420	1	13,140	1	10,300.0

Relative Conductivity, g_r: Iron - 0.17, Copper - 1.0, Aluminum - 0.61.

Usually, this is used in combination with smaller, internal, and more complete shields. Often, such a shield appears as a zone enclosure of opportunity, such as in buried or heavily reinforced structures. The waveform appearing inside such a diffusion zone will generally be a combination of a short spike (possibly associated with apertures) and a longer "tail", related (as before) to the induced skin currents in the conductor.

5.2.6 Apertures. Of course, there are many different kinds of "apertures"; but most importantly, they may be divided as intentional and as unintentional. Perhaps the single worst class of violation of good EMP protection practice arises in the accidental or unintentional compromise of shielding integrity. Anything which interrupts the skin current path on a shield increases its impedance and acts as well as a radiator into the internal region. Hence, the effect of a seam crack is not measurable simply by its physical area, which may be quite small. If it is near a region of high surface current concentration, it can couple energy to the interior many times greater than one might expect. In particular, physical breaks - such as seams and bonds, however well made - represent a constant threat to integrity and protection value.

5.2.6.1 Seams. Of course, it is almost impossible to fabricate a shield as a single, unbroken, electromagnetic enclosure. Large system enclosures can only be constructed by assembling large numbers of sheets or plates. Technically, the contact lines or seam between such single pieces represent potential apertures. The most common large-scale seam techniques involve welding for steel and soldering or brazing for copper. These fabrication methods in themselves place certain minimum thickness criteria on the material. Thinner sheets would "burn through" too easily. So, we see that at least two mechanical aspects already impose minimum thickness requirements, which may, in fact, be greater than required by just the EMP criterion by itself; strength and fabricability. Such thicknesses run from 60 to 300 mils for medium-large military construction. Overlap should preferably be 10-20 times thickness for thin sheets. Butt joints can be acceptably used for thick plate, but this usually requires welds on both sides, with careful probe tests for weaknesses.

5.2.6.1.1 Dilemmas. A system designer may easily be faced with a dilemma. Put in a shield - and it is likely to be much better than is really necessary! But this held still another conflict - the necessary mechanical thickness provides an implicit (and high) dB protection value. Inexpensive assembly methods, such as tack welding, seriously erode that member due to aperture leakage at the long open seams throughout the structure -- it is then not much better than welded rebar. The "good shielding" criterion thus turns out to require continuous and meticulous welding along all seams in order to match the protection value inherent in the material itself.

5.2.7 Gaskets and Bonds. Considering the difficulties encountered with such seemingly "tight" apertures as welded seams, it is no surprise that metal-to-metal contact surfaces, held together by simple mechanical pressure, can constitute serious violations of shielding integrity. Such contact areas are unavoidable at functional apertures (e.g., access doors, service hatches, equipment panels, etc). The terminology of "bonds" and "bonding" suffers from indiscriminate definition. It is used for two hardware topics:

a. Treatment of contact surfaces at extended electromechanical junctions (seam bonds).

b. Low-impedance interconnection of shields and common reference surfaces (bond straps).

5.2.7.1 Seam Bonds. There is extensive literature on all manners of bonding long, continuous, metallic, contact lines. They deal with a range of bonding permanency, from permanent once-made joints through rarely-disturbed service panels, to continuously-exercised doorways. Of course, the latter represents the most difficult problem in dependability and maintainability. The basic mechanical requirements for simple reliable seam bonds is absolute flatness and electrical cleanliness. Neither of these is generally achievable in other than ideal laboratory conditions. The pragmatic hardware problem is then to obtain low-impedance continuous contacts at an acceptable level of "dirtyness" and "deformation".

5.2.7.2 Clean Contacts. Electrically clean surfaces can be readily obtained with pure tin, gold, palladium, platinum and silver. But zinc, plain cadmium, and very thin gold platings are considered as acceptable substitutes. Easily oxidized materials (like Al) should be avoided. Lubricants are capricious. In some cases, they will inhibit

corrosion and oxidation and facilitate good metal-metal contact. More likely (especially motor oils), they will do just the opposite. Any plating is better than none, and controlled roughness is generally better than smooth surfaced (machine scoring and knurling).

5.2.7.3 Pressure Contacts. Of course, roughness is one way to compensate for surface irregularity. An ultimate way to do this is to use deformable conductive gaskets. A good way to understand the pressure contact problem is to consider a panel seam, bonded by means of bolts and flange strips. In the frequency domain of interest here, seams of this type require specific contact pressures of 60 to 100 pounds per lineal inch for 80-100 dB attenuation. Obviously, this form of seam is best for "once-only" cases, which are expected to be broken very rarely, if ever, during the system's life.

5.2.7.4 Electromagnetic Gaskets and Panels. People also resorted to the "gasket" solution for "bonding" peripheral contacts which would only be occasionally broken. It is also useful for irregular or deformable surfaces. There are two "fairly" good types:

a. The flat molded metal gasket which deforms slightly under pressure. This is "throw-away" in the same sense as an engine head gasket.

b. The braided cord gasket. A variety of exotic designs appear on the market. The good ones from an attenuation standpoint utilize deformable metal cores. Unfortunately, these have low resiliency and, at best, can only be reused two or three times. The synthetic core, double braid gaskets are generally more transparent in a given geometry. The single braid types can only be described as "abominable". Braided gaskets are not recommended for exposed, unmaintained situations. It is a lot of work to remove the crud which builds up around them and even then, you will probably be left with oxidized and corroded spots all along the contact line.

5.2.8 Shielded Enclosures. Structural flexibility with reliable shielding effectiveness has been designed into commercially available shielded enclosures. These shielded enclosures are being used for RF testing and measurement. At present, at least, it is not likely that military systems

would employ such components except as accessories in production and testing phases. The prefabricated bolt-together enclosure has enjoyed wide acceptance. However, it does require periodic maintenance. The frame shifts cause open slits and metal-to-metal seam corrosion. Where high shielding requirements exist, serious consideration should be given to the welded seam enclosure.

5.2.8.1 Finger Stock and Doors. Resilient finger stock is a favorite solution for doors and hatches which must be frequently used. Here we see that it should be used in double rows. Some writers suggest that the rows should be staggered for maximum attenuation so that the fingers in one are opposite the slots in the other. At the higher frequencies, this seems reasonable when one considers the radiation pattern of each slot seen as a tiny dipole. Finger stock is probably the most difficult protection hardware to maintain. Traffic inevitably brings with it dirt and abrasion. The doors and frames must be extra stiff if the fingers and the contact surfaces are to maintain their register.

5.2.8.2 Protection Maintenance. This is a good place to emphasize the importance of adequate EMP protection maintenance. There is probably no hardware as susceptible to wear and tear as aperture components. Some of the ways in which this can deteriorate and degrade the protection factors are shown here. Formal procedures should be adopted and adhered to in opening and resealing hatches and access panels -- also for periodic service to personnel and materials entrances.

5.2.9 Open Apertures. Apertures which could be "closed" electromagnetically by means of conductive materials (sheets) and construction similar to the surrounding shield have been considered. The significant problem was the peripheral control. But some mechanical requirements call for a physically open aperture for such things as ventilation, microwave lines, etc. Two broad classes of "solutions" are common for these - screens of various types and "waveguides-beyond-cutoff". The latter can also be used sometimes for entrance passages and doorways to avoid the finger stock problem, where penetration of high frequency content is clearly not a problem.

5.2.10 Screens. Ordinary heavy duty screening is good for the order of 40 dB. The trouble with ordinary materials lies in corrosion and oxidation which can break the contact between individual wires. Electromagnetically, an old piece of screening may be a good coupler. The specially fabricated materials like "electromesh" are treated to resist this action. Hexcel is usually okay, but there have been instances of poor quality control in which the glue between the foils acted as an insulator. True "honeycomb" screening provides the best compromise between shielding and air flow. Where that is important (note cad plated AE/steel type), best results are obtained with honeycomb which has soldered, brazed or welded contacts between foils.

5.2.11 Waveguide Schemes. The "waveguide-beyond-cutoff" is somewhat of a misnomer. Over most of the EMP frequency domain, such a geometry is really behaving more like a quasi-static "field-bender". Indeed, it works even better if we can put a 90° bend in it. The idea is to design it so that its cutoff is significantly well above the high-frequency "roll off" in the environmental spectrum. This is not difficult to do if it is under many feet of earth or if it is already protected by some partial attenuation, such as a welded rebar cage. These situations tend to move the roll off to lower frequencies, as we have indicated before. The approach is fine for ventilation, but don't make the aperture into a propagating structure by running cables through it.

5.3 Penetrations. Again, there are many kinds of "penetrations". Most commonly, one thinks of an insulated conductor passing through an aperture. It may be carrying power or functional signals, but uninsulated, "grounded" conductors, such as motor shafts, can also represent penetrations. Thus, there are two broad classes -- electrical and mechanical. We see here ways in which each can provide paths for coupling and transferring energy from the external to the internal zone. Note particularly that mechanical penetrations can be deceptively protected by innocent-looking bonds, which are really high-impedance couplers.

5.3.1 Electrical Penetrations. The existence of a true "electrical penetration" corresponds to an intentional or unintentional violation of the zoning concept. If an electrical circuit is carefully confined to a single EM zone, then its penetration through a shield does not, in fact, constitute a violation. In principle, it cannot

transfer energy which would not be there in its absence. We make this seemingly simple point to emphasize the necessity for observing zonal hierarchies in proving conductor and cable shielding (as discussed in a succeeding section). But what about unavoidable conductor penetrations such as, for instance, long wire antennas? One thing to do to rectify such situations is to provide entrance protection in the form of filters or active devices (zener diodes, spark gaps, etc). These are discussed in the section on "Protective Devices". These protective devices should be located in vaults or small shielded boxes. Finally, if all else fails, one can isolate that portion of the system (which really goes back to systems and circuit layouts) and simply make its terminal circuits very hard in themselves. So we see that the treatment of purposeful electrical penetrations is not really a "shielding" topic. Table 3 provides a summary of penetration treatments for communication facilities.

5.3.2 Mechanical Penetrations. A conductive metallic penetration may be deceptively protected. Consider, for instance, a shaft passing through a bushing. Here we see two equivalent analyses for the problem of energy transfer through such a seemingly "tight" geometry. In the high frequency domain, it can be treated in terms of a circuit equivalent in which the important features are the bushing contact resistance and bond inductance shunting to the common, shielded reference level. By these avenues, it is not difficult to get a 30 dB leak in a 60 dB shield.

5.4 Cables. This subject tends to bring about the reaction: "Cables are cables -- what can you do about them?" Generally speaking, there is not much that can be done once you have bought them; protection is best incorporated in specification and in installation. Good EMP practice probably costs relatively more in cables than in just about any other hardware area. But without it, "cables" usually turn out to be a lingering sore spot.

5.4.1 What is a Cable? Basically, it is a collection of insulated wires, each of which provides a low resistance (or low impedance) conductive path between two separated terminals. This is also sometimes labeled a "connection".

5.4.1.1 Cable System Design. The development of EMP criteria for cable specification does not necessarily start with the de facto system connection diagrams. Rather,

Table 3

SUMMARY OF PENETRATION TREATMENTS FOR COMMUNICATIONS FACILITIES

Penetration or Component	Peneration Treatments Building with Poor Shielding (less than 15 dB)	Building with Fair Shielding (15-30 dB)	Building with Good Shielding (over 30 dB)
External ground system	Ring ground	Ring ground tied to shield	Building shield with ring or well
Electrical penetrations (method of entry)	Random	Entry panel	Entry panel and vault
Internal ground system	Tree to ring	Tree to ring	Tree to shield
Power lines	Surge arresters and filters	Surge arresters and filter	Surge arresters and filter
Buried communication-cable shields	Connect shield to ring ground	Connect shield to entry panel panel	Connect shield to entry panel
Buried communication-cable conductors	None	Common-mode suppression?	Common-mode suppression
Overhead communication cable	Surge arresters if commingled	Surge arresters, filters?	Surge arresters and filters
Waveguide	Ground to ring ground	Connect to entry panel	Connect to enty panel
Antenna coaxial cable	Ground shield to ring ground	Ground shield to entry panel	Ground shield to entry panel
Other shielded cables, conduits	Ground shield to ring ground	Ground shield to entry panel	Ground shield to entry panel
Other unshielded conductors	Surge arresters as required	Surge arresters, filters?	Surge arresters and filters
Nonelectrical penetrations (method of entry)	Random, but separated from electrical penetrations	Entry Panel? Ground to ring ground	Entry panel, segregated from electrical

it should start in the determination of what is to be connected to what, and in how this is to be accomplished. As we will shortly indicate, much may be done to ease the cable hardening problem by more judicious circuit management. Of course, once the inescapable connection requirements are determined, then one must get to the specific hardware issues.

5.4.1.2 System Configuration Options. One broad category of "fixes" involves reducing the severity of criteria imposed on system cables. We can do this by keeping in mind certain tests for each cable and each wire in it:

a. Do we really need the functions served by the wire (or cable)?

b. Can we accomplish it by a "non-wire" technique?

c. All other things being equal, what options are open for satisfying the connection requirement?

5.4.1.3 High Operating Levels. One way to "ease the strain" in cable protection costs is to work with high power and signal levels in the longer cable runs. If this is not completely possible, it may be more economical to run the lower level circuits in separate and smaller, better-protected cables. As suggested here, do not work with millivolt servos if it is just as easy to work in the volt range.

5.4.1.3.1 Component Distribution. Closely related to operating level is the distribution of components. A simple example appears here: The preference is obvious, all else being equal. Note, too, that the choice reflects on the character of the terminal circuits as well. In the preferred configuration, the pre-amp outputs and monitor inputs will tend to be "harder" simply because they must operate at higher signal levels in their own operation.

5.4.1.4 Carrier Systems. Another way is to go to carrier techniques. Many sensing and control situations lend themselves to this by relatively inexpensive terminal hardware - provided this choice is made soon enough. There exists some older system examples in which the additional criterion of EMP hardening would have easily tipped the scales in favor of carrier systems, rather than DC or low level, self-generating circuits. Carrier systems have the advantages

of permitting floating, balanced conductors, narrow bandpass filtering, transformer isolation, easier nullification, and much more.

5.4.1.5 Circuit Arrangement. Generally, the EMP susceptibility of a cable system is related more to the sensitivities of the terminal elements and circuits than to "break down" or "burnout" limits in the cable itself. Of course, this points at once towards terminal protection but a circuit designer may be able to improve matters by keeping EMP in mind when he considers the terminal element design and the circuit routing through the cable system.

5.4.1.6 The Zoning Role. It was mentioned earlier that different zones may remain isolated, even though connected by long cables. It is worth briefly pointing out why. First, the external propagation impedance (for short pulses) along a long cable is such that it does not significantly alter the external zone coupling from what it would be in its absence. One need only be concerned with VLF (very low frequency, 3-30K Hz) common modes. Second, the propagation attenuation due to radiation or earth damping (if buried) is such that anything originating at A is lost by the time it gets to B in the usual case. Of course, if the cable is involved in a "large loop" geometry, more careful examination is in order. The above "solutions" are somewaht "sophisticated" and are recommended only for the most carefully thought out and controlled situations.

5.4.2 Cable Fabrication. There are all sorts of ways of making wires, insulating them, shielding them, and bundling them up. Some may be excellent for their primary purpose, but not for EMP.

5.4.2.1 Cable Types. When one examines the possible permutations of cable component choices, it is obvious that no detailed case-by-case evaluation is possible. Rather, certain preferable choices in each category of component will be discussed. These can be broken up into two broad categories: Those aspects which influence the control of the effect of external environment, and those which control the inner cable environment, circuit intercoupling, and so forth.

5.4.2.2 Why is the "Exterior" So Important? The dominant mechanism in shielding is the induced surface current. This is concentrated in a surface layer measured by a "skin depth". Skin depth

is the thickness of metal in which the effective "charge packet" is traveling. For typical EMP-like pulses, this may be 5 to 50 mils in thickness. Of course, if we want 60 to 80 dB of protection, the metal has to be several times this thick. As we see here, if it is too thin, the pulse diffuses right in and develops a field to the inner conductors. Of course, if there is no outer shield, this current pulse would be concentrated directly on the outer conductors of a cable bundle. A conducting asphalt is often desirable rather than a non-conducting insulating coat. This conductivity prevents build-ups of the current wave.

5.4.2.3 Braid Transparency. Transfer impedance was discussed previously in the analysis section, but for completeness, it will be considered again in context of cable design. If the wires of an unshielded bundle also interweave, then the "surface current" due to EMP exposure gets transferred inside and all of the circuits share in its pickup. A braided shield also behaves somewhat like this. Besides having lots of holes for field leakage, the braid wires dive in and out. The wire-to-wire contact is not very effective and much of the surface current gets inside to radiate into the internal cable zone. As an "average" example, an RG-8/U cable has about a 10^{-2} current transfer ratio or transfer impedance, for submicrosecond pulses. Thus, at the end of a 50 meter length exposed to a field pulse which induces 10^{3} amps peak current, there will be about a 50 volt signal on the inside.

5.4.2.4 Outer Shield Construction. Here is additional illustration of "good-bad" choices from the EMP standpoint. Like normal enclosure shielding, the thickness is not very critical. One finds that the emphasis is rather on shielding "tightness". Again, we want no "cracks" if at all possible. One brand of "non-tightness" is that represented by a spiral-wound strip - even the double-layer variety. The trouble here is that each turn is actually a turn in a loosely coupled continuous mutual inductance. The contact resistance along the overlaps is too high to avoid some voltage buildup per turn. This type of shield acts as a passably good coupler between external environment and internal wires. Conduit, when properly installed by threaded connection or welded joints, behaves very much like an additional solid-metal outer conductor. When needed for other reasons, such as blast resistance or code requirements, it is probably the cheapest in terms of added EMP cost.

5.4.2.5 Quality Control. These problems can be compounded by loose material specification, shoddy factory control, and lax acceptance criteria. Shielded cable deliveries should not be judged for payment by stock clerks. Too often one finds newly delivered cables in which the outer shield is badly oxidized or even corroded. If the construction is such that good shielding depends on good internal contact, you are clearly not going to get it.

5.4.2.6 Outer Jacket or Sheath. The data on the value of an insulated outer jacket on EMP/cable coupling remains debatable. There is some evidence that it can reduce the skin current in threat regions of direct field exposure and coupling. On the other hand, contact of the outer shield with a conducting earth or the use of a conducting medium has also been shown to provide propagation damping for a pulse originating elsewhere. It can also be argued that an outer jacket can "pinhole" through if the local field is too high. The governing factor would appear to be durability to this end, lead sheathing or neoprene jackets seem to provide lifetimes commensurate with normal useful systems lives. Of course, the fabrication and installation cost factors favor neoprene today. This is an area where further resolution of design considerations appears desirable.

5.4.3 Damping Schemes. EMP propagating in the direction of buried cable can cause a "traveling wave" voltage build-up. Here are some ideas on how this can be minimized. Besides "grounding the sheath", there are other steps which can be taken to alter and suppress the transmission of fields along a cable. Suppose we look at a cable as the central conductor of a transmission whose outer conductor is very far away. Any change in the transmission impedance radically will produce reflections. Some of the energy will go back where it came from; thus, the insertion of perpendicular conducting baffles. This has been successful in many cases suppressing pulse interference in nuclear test cable systems. Anything we can do to enhance the fields in a "lossy" material (such as wet earth) will increase its attenuative effects. This is embodied in the introduction of ferrite ring "field concentrators" around a cable. If the ferrite is made lossy as well and is located at the base of a baffle, an ultimate degree of feasible attenuation can be achieved, as shown here. A "poor man's version" of the same thing consists of a spiral corrugated outer shield with interwoven high-μ wire. At the moment, the above approaches are in the "good ideas" category, and little information exists on a quantitative basis.

5.4.4 Cable Terminal Treatment. After many years of noise and malfunction, systems designers learned to connect the outer shield of a cable to the metal can or framework of the equipment. The use of anodized shells for multi-pin connectors has created this problem. The only feasible way to maintain a good "system ground" is to carry the ground wire through one or several of the connector pins. Of course, they did that poorly, too, by taking the connection through a plug and socket pin, using a high inductance jumper. It isn't merely the insertion of the inductance which "kills" you, but the propagation discontinuity causes a pulse reflection at this point as well almost doubling the voltage induced across this interface. As suggested here, this injects a pulse into the signal lines because of local capacitive effects.

5.4.5 Plugs and Sockets. The right way to do it is to use the entire connector shell as the contact element. The socket should likewise make peripheral contact with the equipment shield or container. In effect, one wants to approach the transmission effectiveness of UHF waveguide hardware, as far as the shield is concerned. Differences in good overall shield design are often overridden by poor connector design.

5.5 <u>Conduit</u>. When properly installed, conduit is easily the best "outer shield" for cable systems. The principal problems arise at segment contacts. Again, cleanliness and careful assembly are essential. Rusted and corroded threads and bushings will introduce series impedances along the conduit's length. Welded joints are best, but expensive. Welding is almost the only dependable way to deal with the conduit terminals. Normal clamp rings make contact at only a few points, at best. All too often, there are some loose ones left behind. The conduit ends are particularly sensitive system points because here the exterior transmission impedance changes. Pulse currents flowing on the outer surface must be redistributed onto the equipment shield. If relative movements between exterior conduits and shielded buildings are expected (due to shocks or earth movement), the use of bellows, convoluted sections, or multiple knitted socks should be considered.

5.6 <u>End Boxes</u>. Cable terminal treatment by means of lumped-element "end boxes" is popular because it accents the illusion that "you're doing something about EMP". Usually, they contain elements intended to suppress EMP pickup by the cable wires themselves. This is fine, as

long as the final circuit reference level can be maintained with the internal zone. This then requires that the terminal box be integral with the interzonal boundary, as shown here. Too often, such boxes are mounted on the wall with two self-tapping screws, or are connected to the equipment can by means of a foot-long braided jumper. Cable end boxes have also been effectively used for marginal retrofit cases, in which a more thorough "solution" would have been dramatically expensive.

5.7 Internal Treatment and Circuits. In some systems, such as communications, the cable cost is a large item, and the cable specification has to be detailed to achieve maximum service return. The internal conductors are usually specified according to the degree of environmental isolation which each service or function requires. The external shield then provides just the minimum needed by the least sensitive circuits. Frequently, advantage is taken of the specifications imposed by service performance requirements. Thus, a broadband coax requires a solid outer conductor and good lead connections for best performance.

5.7.1 Twisting and Shielding. For medium level sensors and medium bandwidth circuits, adherence to zoning and circuit reference criteria may suffice internally. This means provision of separate return reference wires (independent two-wire circuits) which are fabricated as a twisted and shielded pair. Braided shielding is often sufficient here. Broadly, these practices are generally commensurate with requirements for intercircuit isolation ("crosstalk").

5.7.2 Balanced Isolation. As indicated before, if a system lends itself to carrier techniques, then 30 to 40 dB may be gained in protection value by using balanced cable circuits with terminal isolation transformers. Conversely, the requirement on the built-in cable shielding may be that much less severe. The advantage of the "carrier" approach resides in the case of obtaining balanced isolation transformers which operate over a "limited bandwidth". Extra filtering may also be required to assure that the bandwidth is restricted to the "limited bandwidth" of the transformer.

5.7.3 Terminations. It is good practice to consider multi-layer shields and common mode (phantom) circuits as independent energy transmission lines and to terminate them accordingly. As indicated before, precision in doing this is not important - the main thing is to provide an energy dissipater so that the pulse won't "rattle" back and forth.

5.7.4 Power Supply and Control Circuits. Some "connections" must be DC or non-carrier AC. If these can be treated by means of terminal filters and by high-level operation, then (together with carrier signal techniques) the EMP requirement on the total cable package can be a minimal one.

5.7.5 Hierarchies and Zone Loss. For short cable runs, one has to be somewhat meticulous about connecting successive shield and conductor "layers" to enclosures and circuits of corresponding zone level - no "criss-crossing". Obviously, one may otherwise end up by depositing high-level environmental "noise" (or EMP) into low-level system elements. It is also "bad practice" to "carry grounds" on the outer skin in short runs, an easy temptation. For long runs, it was indicated that zonal identity tends to "get lost" in the damping due to radiation and medium coupling. At this time, this is more a matter of experience than theory. By "long", is meant one mile or more.

5.8 Grounding is a complex topic, but can be oversimplified by dividing grounds into the interior and exterior grounds as indicated. To oversimplify somewhat for clarity, there are:

a. Grounds/earths/buried conductors/rails/pipes outside (exterior).

b. Grounds/reference nodes/buses/equipotential grids inside (interior) for partially or well-shielded equipments.

"Grounds" are needed for almost "everything", but are often a major source of EMP pickup.

5.8.1 Ground Semantics. It is worthwhile reviewing briefly some of the terminology in "grounding" or "earthing". The term "ground" is often taken to mean a purposeful electrical connection to an exterior buried conductor. It is also used to identify circuit connections to the "common" or "bus" side of a circuit or to chassis, racks or large shields forming an "inside ground". Basically then, the orthodox/"outside ground" identifies an attempt to connect, in a field-significant way, to the large, but poor, rational conductor which covers the earth's surface. This topic of "outside grounds" is probably the most ambiguous in the business. The idea of "grounding" as a "good thing to do" originated decades ago when it was found that:

a. Power systems were less dangerous with controlled grounds.

b. RF systems behaved more stably with controlled grounds.

c. Antenna radiation improved with controlled grounds.

d. Lightning killed fewer people with controlled grounds.

But there is a broad range of types of grounds and an equally broad range of quality.

5.8.2 Why is EMP Concerned with Outside Grounds? There are at least three reasons for considering how EMP and exterior grounds interact. First, there are long wavelength threat components -- especially from surface bursts -- with which ground circuits can meaningfully couple. Second, system grounds are essential for any number of other reasons; e.g., noise reduction, reference point, etc; hence, their EMP coupling is a germane issue. Third, it has been pragmatically established that grounds make a noticeable difference - good and bad - in nuclear test instrumentation. Of course, if a grounding system can be put to advantage in EMP control -- so much the better. But this may be in conflict with other grounding requirements; i.e., lightning, power, etc.

5.8.3 Ground Concept. The basic idea of a ground is to provide an equipotential distribution between the dominant structural members of a system and the surrounding natural environment. That "equipotential" concept raises some questions. Clearly, it is "perfectly" valid only for the ideal case of:

a. Static fields.

b. Infinite conductivity.

c. No current flow.

Obviously then, if a "ground" seems to improve a real, non-static condition, it is because it does change the external field distribution. A current flow must necessarily exist in the ground conductors in order to do this. Hence, real grounds always represent a departure from the

ideal. The point is that the external field distribution is a more tractable one in a "good ground" situation. Some of the mythology of the EMP folklore concerns the improvement realized by avoiding "outside" ground loops by the substitution of single-point straight cable runs. In either case, EMP can induce substantial amounts of EMP current flow onto the cables or conductors. The outside ground loop does tend to enhance the lower frequency components and prolong the duration of large circulating currents. The straight run tends to dump extra current into the interconnection point. In either case, the pickup is sensitive to angle-of-arrival, ground parameters (σ and μ) and many other details.

5.8.4 Ground Quality. The best way to evaluate the exterior ground concept is to point out the nature of its limitations. Some systems could not realize any advantage from grounding. For instance, one can think of a configuration in which the interior zones are so well isolated from the exterior that no external changes can be sensed inside. And, of course, there are the inapplicable cases like missiles in-flight! Most systems are not that opaque. By proper design, the field and current enhancements can generally be suppressed arising from exterior grounds. There are two basic limits where grounds are of little value:

a. A ground connection so long that it introduces appreciable impedance in the ground circuit.

b. Dominant wavelengths so short that the system is physically the larger.

5.8.4.1 Exterior Ground Resistance and Transient Impedance. These concepts are perhaps the least understood in contemporary electronics engineering. To place them in their proper perspective, it is essential to understand the electromagnetic circumstances in a current-carrying conductor. <u>Most of the EM energy exists in the field external to it.</u> The energy content in the "skin current" on the conductor is usually a few percent. Thus, the effectiveness of a "ground" for transients or for RF in the LF to HF domain depends, in part, on the coupling of that external energy into the earth and more significantly, <u>its absorption</u>. By this, we mean <u>conversion of EM energy to heat</u> (in the earth) by I^2R heating, of course. This is a very tiny number in typical cases $\sim 10^{-8}$°C rise. In many cases, the best choice

might be to maintain a single-point exterior ground concept consistent with the position of the interior single-point ground for a shielded system. The power, lightning, safety, or crypto ground should be made as compact as possible, thus avoiding long conductor runs capable of collecting or enhancing EMP.

5.8.5 Inside Grounds. To understand why "inside" grounds are different, let us review a few facts. With a good shield, magnetic field and coupling effects tend to dominate. Option: Use a good shield and minimize magnetic field couplings and common impedance "voltage sources" by use of a single-point ground. The shield "goodness" must be such that the wavelengths of the principal penetrating waveforms are always large compared to the longest ground cable length.

5.8.5.1 Interior Grounding Systems. There are a wide variety of geometrical arrangements for "connecting to ground". Figure 9 shows a typical ground system. Here, we identify several of the accepted connection geometries:

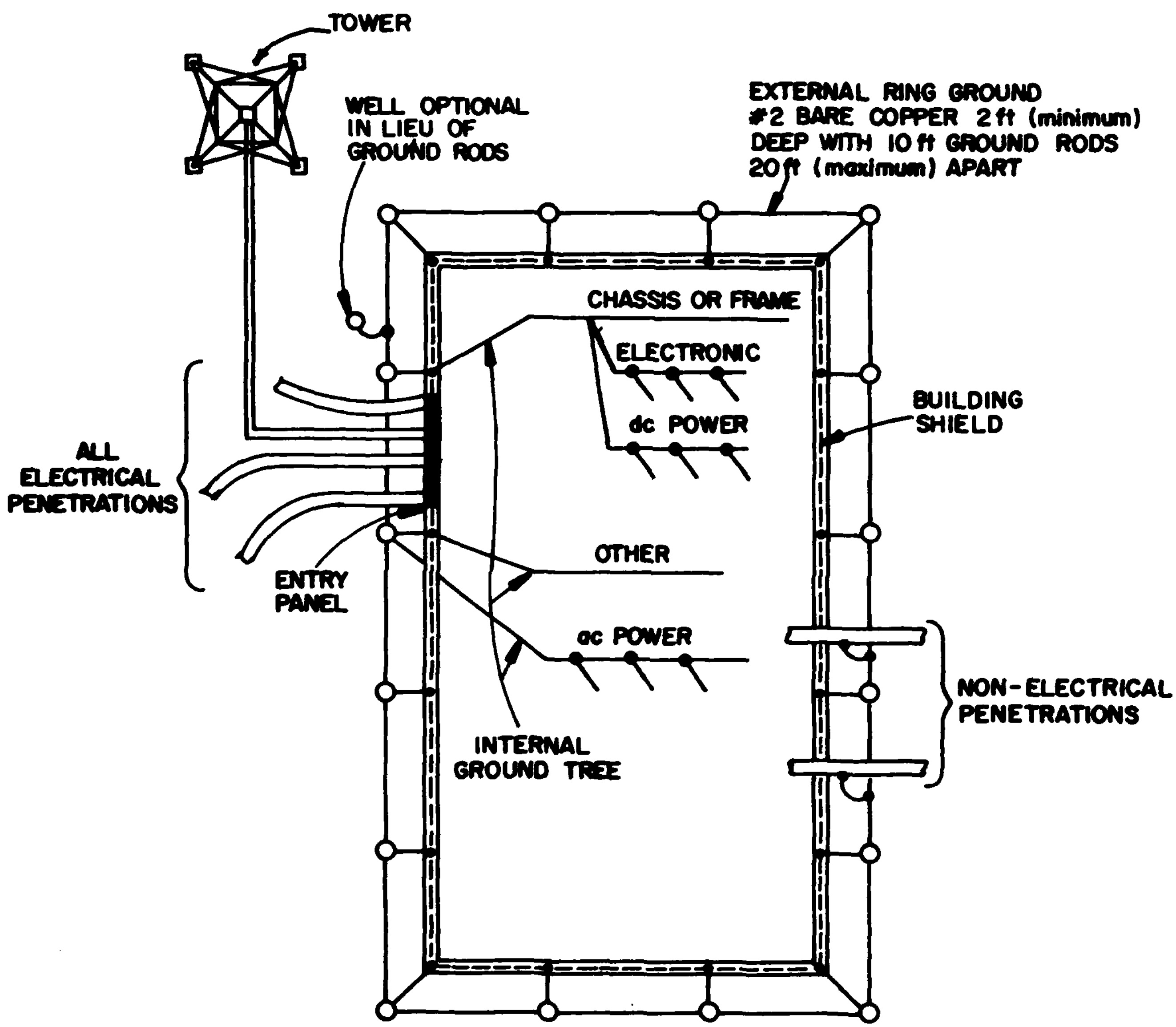
a. "Crow's Foot" or single-point. Probably the wisest choice in a "bleak" situation, since it minimizes coupling in the ground connections proper.

b. Fishbone. The lower level (higher sensitivity) circuits should usually be at the "far end", where "ground currents" are lower.

c. Multipoint. Note the opportunities for ground loops and common impedance IZ common voltage rises.

d. Floating Grounds. Often employed where a single point ground is impractical and where a multipoint system could cause trouble. Here, each subsystem case assumes its own potential without ill effects provided that good isolation (common-mode rejection) is realized.

5.8.5.2 Internal Grounds. It is very easy to get carried away to the point of providing good coupling between high energy circuits and high sensitivity components by grounding everything. The reference node design technique tries to ensure that each electrical system is treated as a complete, independent circuit entity. Bonding between each level can then be introduced selectively and carefully.



TYPICAL RING GROUND SYSTEM
FIGURE 9

5.9 Bonds.

5.9.1 Interzonal Bonds. As suggested here, the reference bond between successive zones should be approached with much the same criteria in mind as for any circuit connections. In particular, minimize BA. This means that the connection should be close to the main conductor runs and that there should preferably be just one of them. In some cases, the "bond" may be provided by massive and distributed structural elements. This represents an "opposite extreme" which can be advantageously used. But then, it becomes exceptionally important that these extended contacts remain electrically "good" -- no loosening of the bolts, or oxidation between the plates, etc.

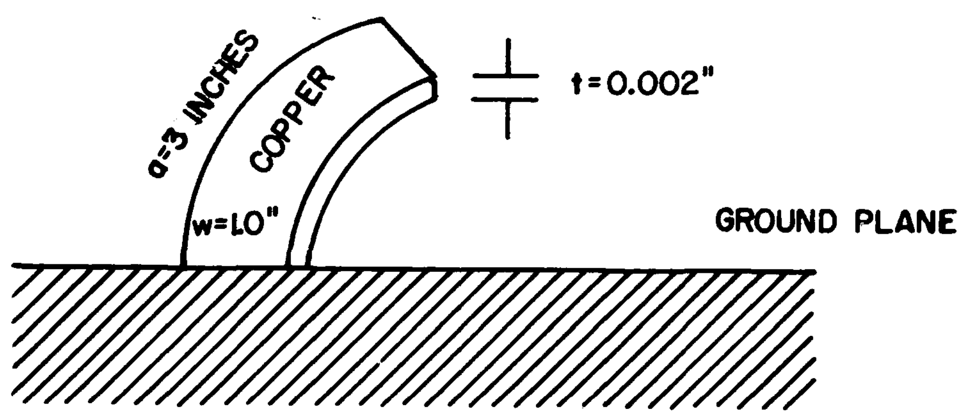
5.9.1.1 Bond Straps. Bond straps or "jumpers" usually appear in a system as a result of faulty initial design. They can only be justified a priority, for conditions where unusual flexibility or frequency disconnection are unavoidable. The best way to connect things together is to bolt or weld them to each other and not use a bond strap at all. But if you must, Figure 10 shows what a bond strap looks like in simplified mechanical and electrical forms. A circuit analysis is presented in the handbook. Typical good bond straps have inductances in the order of 0.02 Hz. It is difficult to work effectively with much less than this, because then you might as well bolt the parts together. Much more, and you're likely to get sparks between them.

5.9.2 Good Bond Strap Practices. Obviously, anything which lowers the reactance of a bond connection improves its performance. We see here the "good" directions. Of course, ultimately, this would translate into a continuous sheet connection, and we would really have a piece of shielding. Hence, there is an economic break point at which "more bonds" should really translate to "component redesign".

5.10 Protective Devices and Techniques. Up to now, protection methods which, in one way or another, deal with the coupling of the threat pulse environment to a system and its circuits have been discussed. One might very well ask: Why was the discussion of filters, limiters, and so forth placed at the end? Often one hears that the "solution" to an EMP problem was a spark gap, a line filter, or some other lumped element placed at one critical point. Each expression tends to overlook the many other environmental

BOND STRAPS

t = THICKNESS
a = LENGTH
w = WIDTH



TYPICAL BOND STRAP
FIGURE 10

protection features which the system may have had built into it, intentionally or not. These made it possible to isolate the ultimate weak points to a number, type and susceptibility, which could be successfully rectified by a limited and feasible lumped element approach. In general, protective devices and techniques alone could not protect a totally "naked" system at finite cost. This document will not provide specific protective devices by manufacturer part number, etc., but will provide a short introduction into use, purpose, name, etc. Various references in the Bibliography, such as 5, 6, 12, 18, 19, 28. and 29 should be consulted for more specific information on protective devices.

5.10.1 What is a Protective Device? Basically, it is a "lumped element" both in hardware and in software. In hardware, it is most usually represented by a "black box" insertion in a circuit. But it can also be a mechanical contrivance inserted to interrupt a non-circuit conductive path. In software, it can be represented by a functional insertion, such as a contingency command, or a sensor-controlled branching in an operational sequence. In summary, it is an isolated object or action which is inserted specifically to counter an undesirable EMP consequence.

5.10.2 Basic Protection Element Concept. This summary definition at once lends to a very basic specification concept for a protection element. An efficient protection element has a performance characteristic which is inverse to the susceptibility of the hardware or function which it is intended to protect. One consequence of this is that such an element must then be able to stop or absorb the excess energy (or the erroneous message information) which would otherwise have reached the next system component. Usually, it would not do much good to protect a solid-state device by means of a second device of similar susceptibility.

5.10.3 Categorization. Some EMP protection schemes suggest that their designers were unaware of more appropriate hardware schemes. It thus seems worthwhile to categorize and identify the many devices and techniques. The first two are self-evident - hybrid devices combine voltage or current limiting with filtering. Operational or functional schemes involve various ways of interrupting system operation and/or temporarily suppressing its sensitivity to reduce the threat consequences. Unconventional methods

include schemes for actuation or communication not requiring conductive paths or significant apertures.

5.10.4 Circuit Isolation. Passive and active lumped-element "boxes" are examples of isolation devices. They couple one circuit to another only in the signal regime of interest. Limiters do this by restricting the range of linear transmission filters, by similarly limiting the frequency domain. There are a number of useful passive elements besides filters, as will be discussed next.

5.10.5 Inductive Devices. Two inductive devices are particularly useful in common-mode suppression, as may be required on cable connections between equipment in two different EM zones. Both are extensively used in nuclear test instrumentation. In a bifilar choke, the push-pull or desired circuit paths carried by the multi-conductor cable are only weakly coupled to the core, whereas the common-mode carried by the whole bundle is strongly coupled. Hence, the common-mode is strongly discriminated against. The required series inductance evidently depends on the desired attenuation and on the predominant frequency content. The balanced mode transformer similarly discriminates against common-mode energy, but it is limited to HF application, of course.

5.10.6 Passive Devices - Filters. The most common passive, lumped-element device is the terminal filter. It is basically a black-box with input and output connections for insertion into an otherwise continuous two-wire circuit. Its insertion loss is chosen for least attenuation in the frequency domain of normal circuit operation and maximum loss in the domain of maximum "noise" content. Note that the intercepted energy has to go somewhere. Maybe it is reflected back into the input system, to increase the EMP level there. Better that it should get "dumped" as heat in an internal filter resistance. This implies a preference for "lossy" filters, of course.

5.10.7 Butterworth Filters. Here is a typical working example of a filter analysis for a very severe exposure situation. One might experience something as bad as this for a completely "naked" megawatt level power line.

5.10.8 Device Construction. The construction and installation of a protective device is often as critical as its design. If we think of a filter as a controlled RF barrier,

then it is clear that its input and output must be isolated from one another. A good filter (or other device) is usually constructed in three separate electromagnetic sections; an output compartment, device compartment, and an input department. Most frequently, filters and limiters operate "against ground"; that is, the "return" side of the protective element is well bonded internally to the filter case. Good filter design and adjustment takes into account whatever mutual coupling may exist between input and output within the central component compartment. This convention comes from the customary circuit practice of using "case" as the reference node in small and medium size system elements, both for single-ended and balanced systems.

5.10.9 Device Installation. Obviously, the same care in isolation is called for in installation; much of the device's value is lost if the output side can "see" the input side. In the "right way", the filter case must make a tight peripheral contact so that there is no "hair-line" aperture and so that the common reference impedance is nearly zero. This is also important if one is to obtain the benefits of the designer's and manufacturer's ratings. Evidently in such installations, the internal EM zone makes a detour into the device's output compartment.

5.10.10 The EMP Box. In some installations, particular care has been taken to isolate such entrance protective devices. This is the origin of the "EMP Room", sometimes ostentatiously displayed as the "solution to EMP". On older, "unprotected" systems, one finds similar entrance spaces, simply labeled "cable termination vault". When properly outfitted, these installations have value in decoupling the exterior from the interior environment and in reducing the secondary effects of non-linear operation of the protective devices themselves.

5.10.11 Active or Non-linear Devices. Partly in consequence of lightning and power-surge problems, a broad gamut of non-linear protective devices have evolved. Many of these are applicable to circuit EMP problems, perhaps with slight modification. The most serious defect in commercial protection devices is the penchant for using "pigtail" type connections between terminals and the protection element itself. These generally present at least as high an impedance to an "EMP" as does the circuit itself. Many of these devices would be useful for EMP protection if they were simply "cleaned up" by using low-inductance bond

straps and adequate connection contact areas especially to the case (or "common reference") side. In most cases, the signal circuit should be taken through the box; the protective device should not simply be shunted at a single terminal point.

5.10.12 Hybrids. This is the most favored "lumped-element" solution, in that is combines the better features of active and passive elements. The filter element suppresses "hash" below the breakdown level, as well as suppressing hash generated by the active device itself. The series impedance preceding the surge arrestor is a necessary component to assure appropriate limiting; in some cases, the surge impedance of the transmission line can suffice.

5.10.13 Types of Non-linear Devices. This represents a listing of "possible" devices for EMP application. One problem with most non-linear mechanisms is "hang-up" or hysteresis in the activation/deactivation cycle. Thus, it is difficult to use them in circuits in which normal operation may involve levels approaching "breakdown". In some cases, it is impossible to avoid some degree of "cold restart" capacity such as might be provided by electromechanical relays or by "crowbar dumping". This applies particularly to high power level systems, such as utility distribution or radio transmitter outputs.

5.10.13.1 Consequences of Non-linear Operation. Nonlinear devices are not unmixed blessings. We already indicated under filters that the EMP energy has to go somewhere. This remains true for active elements as well. Furthermore, one is also faced with the feature that the switching operation itself can be a source of unwanted EM energy (e.g., RFI). This is particularly true if the associated circuits contain significant EM energy in normal operation. When the device switches, it must inevitably cause some change in effective circuit impedance and, hence, in operative current distribution. In addition, the switching function may generate a spurious pulse in the circuit itself. This is particularly possible if the switching occurs on a time scale short compared to that of the normal operational signals in the system; e.g., on the fast-rise "front" of an induced EMP signal. This is one of the strongest reasons for using "hybrid" lumped elements.

5.10.13.2 Spark Gaps and Gas Diodes. These both depend on initiating conductive breakdown in a gap. Spark gaps are bipolar in operation, have low voltage drop when conducting, and are simple and easy to make. But they do not extinguish without removal of almost all power, and their breakdown characteristic is such as to generate considerable HF "hash" in their vicinity and in the connected circuits. Gas diodes operate as smaller voltages and "turn on" less noisily, but they cannot carry high currents for long and tend to be capricious as to long-term reliability.

5.10.13.3 Zener and Silicon Diodes. These are generally smaller, lower power devices. They operate effectively in the voltage-current range of solid state circuitry, so that they are extensively used for such circuit protection. They are voltage-limiting in action (rather than voltage-reducing). Silicon diodes "clip" more effectively their "plateau" is flatter. Their operating voltage is generally low - a few volts - and the introduction of "hold-off" bias can be an inconvenience. They are generally high-capacity devices, so that there are limits as to the circuit frequency range of applicability. Also, the semi-conductor devices have definite limits on the joule energy handling capability.

5.10.13.4 Thyrites. This may be used for "brute force" problems. It can be used for good transient response. It is basically a non-linear resistance with unusually high power-dissipation capacity. It can be made "simple" by virtue of using circuit impedance as part of the limiting mechanism, but it is <u>not</u> an "absolute" limiter - it only "rounds off" a transient peak.

5.10.14 Fast Relays. These relays operate in less than one millisecond. Their principal value lies in interrupting protection circuits in order to limit the energy dissipated in the faster protection devices, and in order to initiate restoration to normality from a breakdown condition.

5.10.15 Crowbar Circuits. In these systems, a high-power rating device is operated by a subsidiary sensing/trigger circuit. Thyratrons, ignitrons, and spark gaps have been used for the "crowbar". Sensing can come from the circuit itself, from a "threat" sensor (see last topic), or from an auxiliary breakdown device (e.g., corona optical sensor). Crowbar circuits are often used to activate the normal system protection interlocks. For example, EMP

could "fire" a spark gap or cause an arc-over in the transmitter output. This arc, if not extinguished, could cause excessive plate dissipation in the output tubes. In this case, a thyratron can be "fixed" across the transmitter DC supply to activate the circuit breakers. The thyratron is activated by a corona-sensing photocell near the spark gap or, better yet, by an impedance sensing circuit.

5.11 Circumvention Techniques. Some EMP problems are physically sufficiently formidable and "hard-nosed" hardware treatment is simply impractical. This can be particulary true in retrofit - perhaps for no other reason than the complications involved in removing system elements from operational status. The basic principle involved in "circumvention" is to reduce the time period of high vulnerability so as to reduce the probability of coincidence with threat exposure. Obviously, human intervention is (almost) out of the question. (The only conditional situation here applies to systems intended for post-strike activation.) There are two broad classes:

a. Non-threat-specific or duty-cycle techniques.

b. Threat-specific or nullification techniques.

5.11.1 System Constraints. If we "gate down" a system in real time, there is at once an implication that the operational sequence execution would take place on a comparable timescale and with appropriate bandwidth. Only the more modern and sophisticated systems have such capabilities (i.e., 10 μsec stepping time). But, such systems are also open to a number of protection response options. For instance, the system response can be programmed to depend on where in the sequence the threat appears. It can overlook the threat if it is in a relatively invulnerable mode. It can stop and restart from some previously determined early stage or cancel a number of previous commands. It can similarly pause or hold, test for status validity, and start up again. Older or more primitive systems generally cannot be desensitized "in time". Usually, one must assume error or interruption, when a threshold field is reached, and simply restart the sequence. (This presumes that the system is hard enough to avoid permanent damage, of course). In some cases, one may have the option of programming a separate sequence validity test which can negate or enable the mission sequence at some later stage.

5.11.2 Non-Threat-Specific Schemes. Duty-cycle schemes are generally permissible when the exact threat response time is not critical. If a particular system step requires 11 μsec to execute, but may be done anytime within 10 μsec, then one may gain a reduction factor of 100 in threat coincidence probability by suitable cycle suppression. Both random and synchronous schemes have been considered. The synchronous scheme lends itself to certain forms of bandwidth reduction as well. A variety of gating and switching techniques can be applied for disabling circuit inputs during the "off" periods. Redundant message transfer is another alternative.

5.11.3 Threat Specific Schemes. An active nuclear threat may be sensed in a number of ways. Let us confine attention to "prompt-spike detection". The basic reason that this works for EMP is that the waveform peak inside a system is generally much broader and, hence, later than outside. In principle, one can use the exterior-sensed signal to "gate down" the execution sequence before the internal environment reaches error or interruption levels. The biggest problem with this scheme lies in "false triggers". Experience indicates that it is almost essential to couple two different prompt sensors in coincidence in order to avoid almost continuous system inhibition due to non-nuclear noise. By "different", we really mean different, such as an EMP antenna and a photoelectric unit.

5.11.4 Non-electrical Schemes. Some relatively simple mechanical schemes have been applied to zone decoupling problems such as non-conducting shafts in M-G sets and insulated solenoid actuating switch.

5.12 Economics. Finally, a word about EMP hardware costs. The lack of meaningful improvements in EMP hardware methods is partly a consequence of its frightening economics. This fear of costs in itself engenders higher costs, since it develops so few reliable "cost effectiveness" experiences. It is fairly clear that meticulous adherence to appropriate known hardware techniques adds noticeably to system costs. At present, there seems to be no reliable avenue for safe compromise. Most economical and effective protection is realized if the hardening effort is an integral part of the original system design.

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